Headquarters U.S. Air Force

Integrity - Service - Excellence

Pragmatic Expectations for NAPL Source Zones

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Pragmatism

(Williams James)

- **Meaning of conception is sought in practical bearing**
- **That the function of thought is to guide action**
- **Truth is preeminently to be tested by its practical consequence**

A National Debate Regarding NAPL Source Zones

- RCRA Refinery Workshop - EPA/API - Denver (1997)
- Theis Conference What is Success - NGWA Jacksonville (1999)
- Pragmatic Expectations for Source Zones - Solvents Consortium - (2000)

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Objectives

- Focus our individual site management and research efforts
- Drive a shift towards more pragmatic expectations for management of DNAPL source zones.

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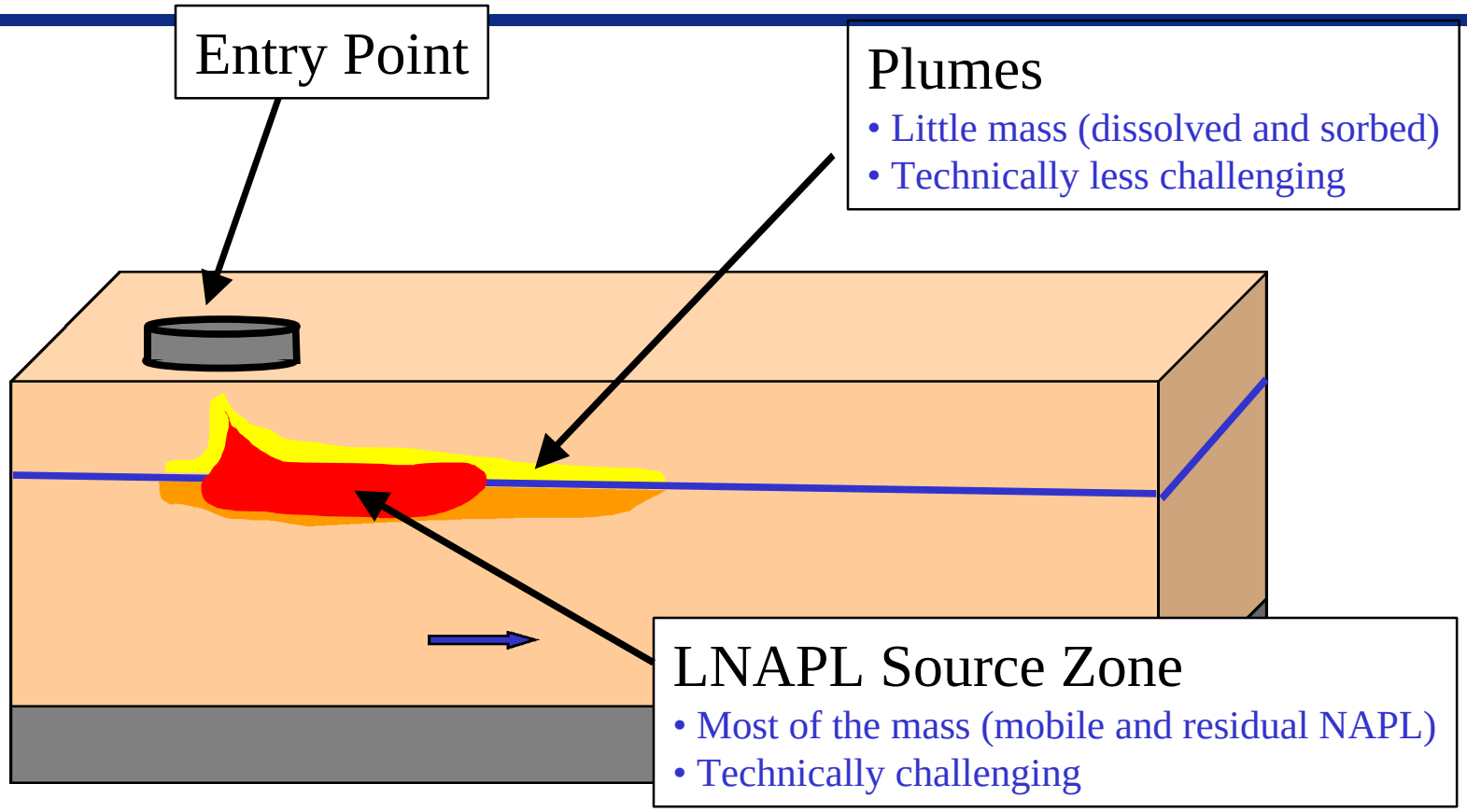
Terminology and Concepts

Conceptual Models



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Remedies

- **Containment**
  - **Active (e.g. physical/hydraulic containment)**
  - **Passive (e.g. reactive barriers)**
- **Source Zone Cleanup**
  - **Remediation (Junk term - any mass removal)**
  - **Restoration (Pristine)**
  - **Renovation (Fractional depletion with a tangible benefit)**

General Source Zone Options

- Mass Recovery (forced advection)
  - Physical recovery
  - Chemical mobilization
  - Thermal mobilization
- Mass Destruction (mass/heat transfer to NAPL)
  - Biological oxidation
  - Chemical oxidation
  - Thermal destruction

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Source Zone Goals

- **Restoration**
  - MCLs in source zone
  - Very high levels of mass removal
- **Renovation**
  - Stabilize LNAPL
  - Reduce Source Longevity
  - Reduce dissolved flux from source

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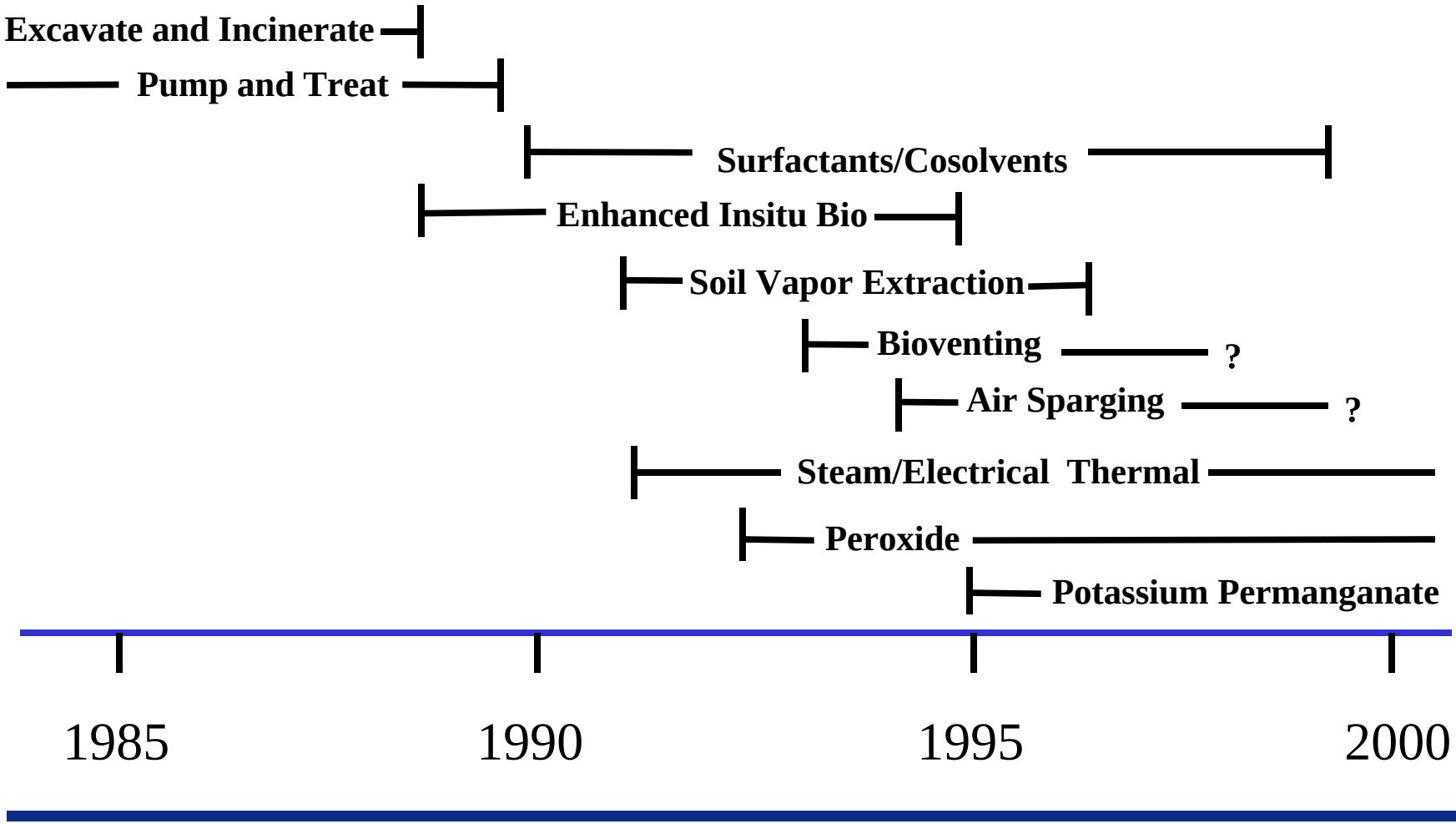
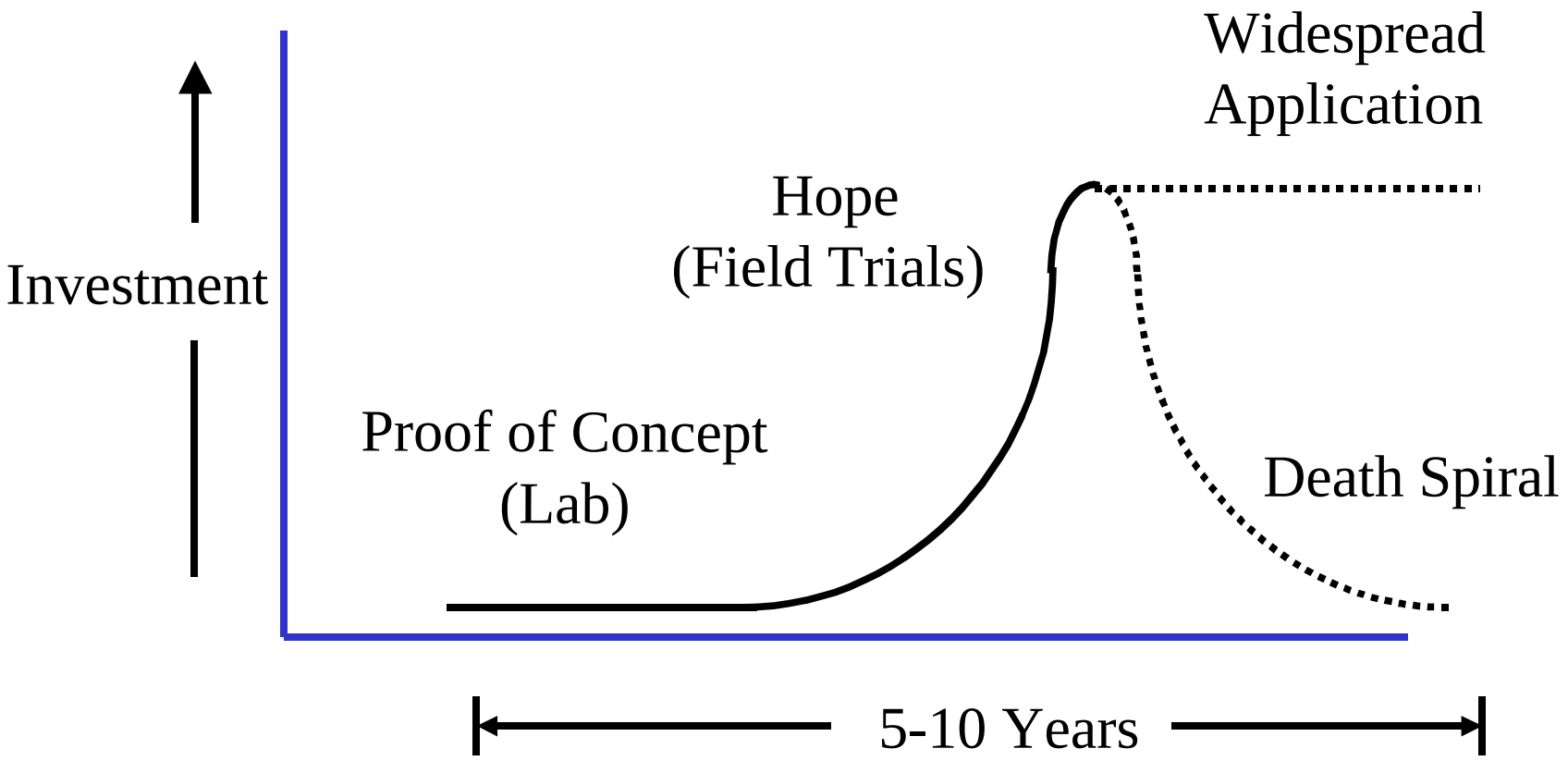
Source Zone Restoration Technologies



Life Cycle of an Innovative Source Zone Technology



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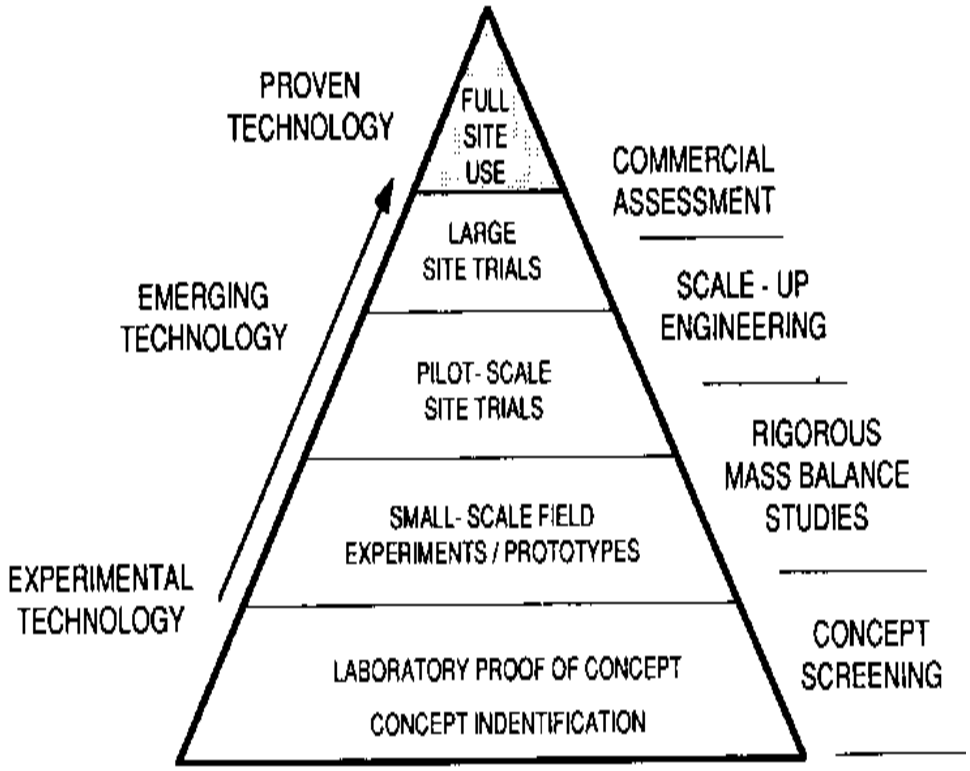
Technology Status



Pankow and Cherry 1996

No large DNAPL zone has been restored therefore all source zone restoration technologies are experimental

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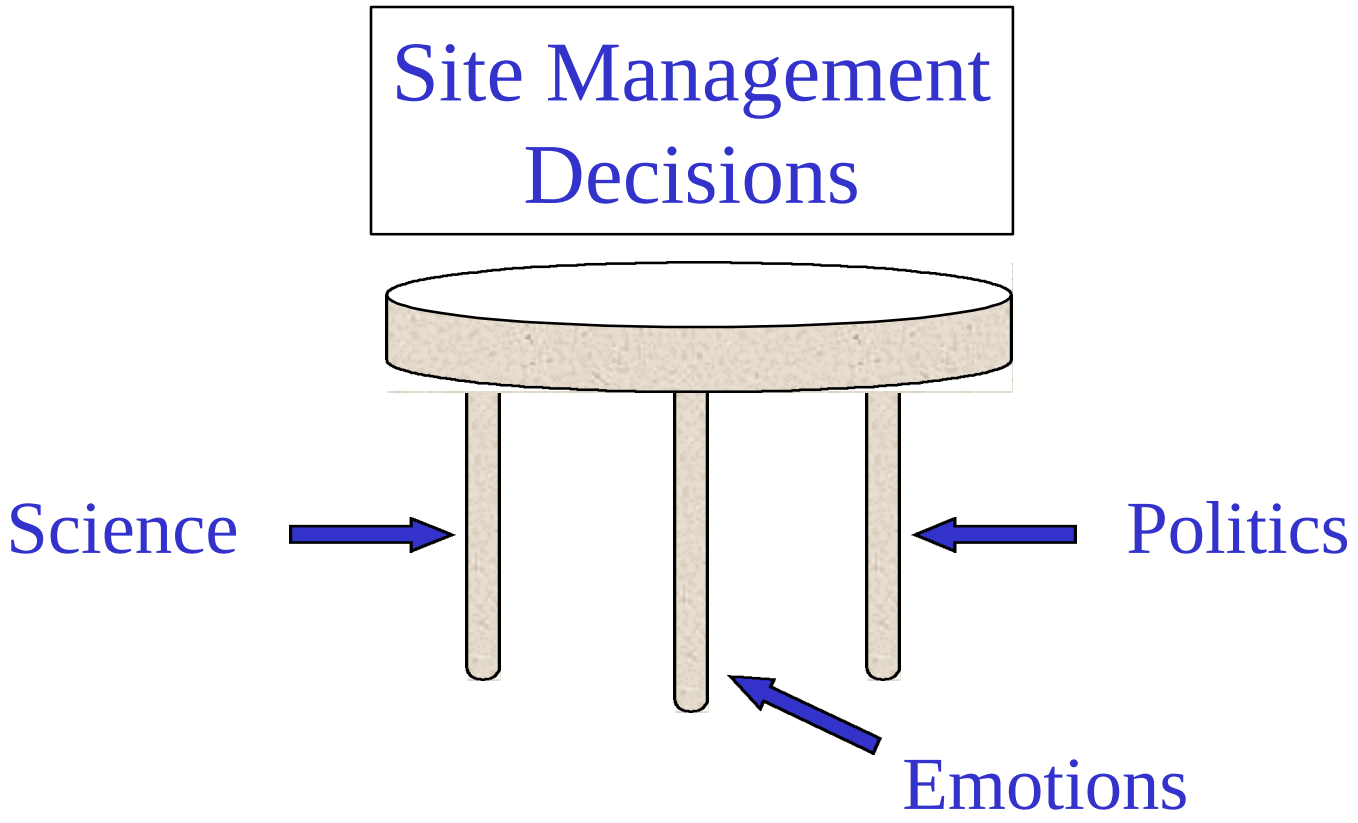
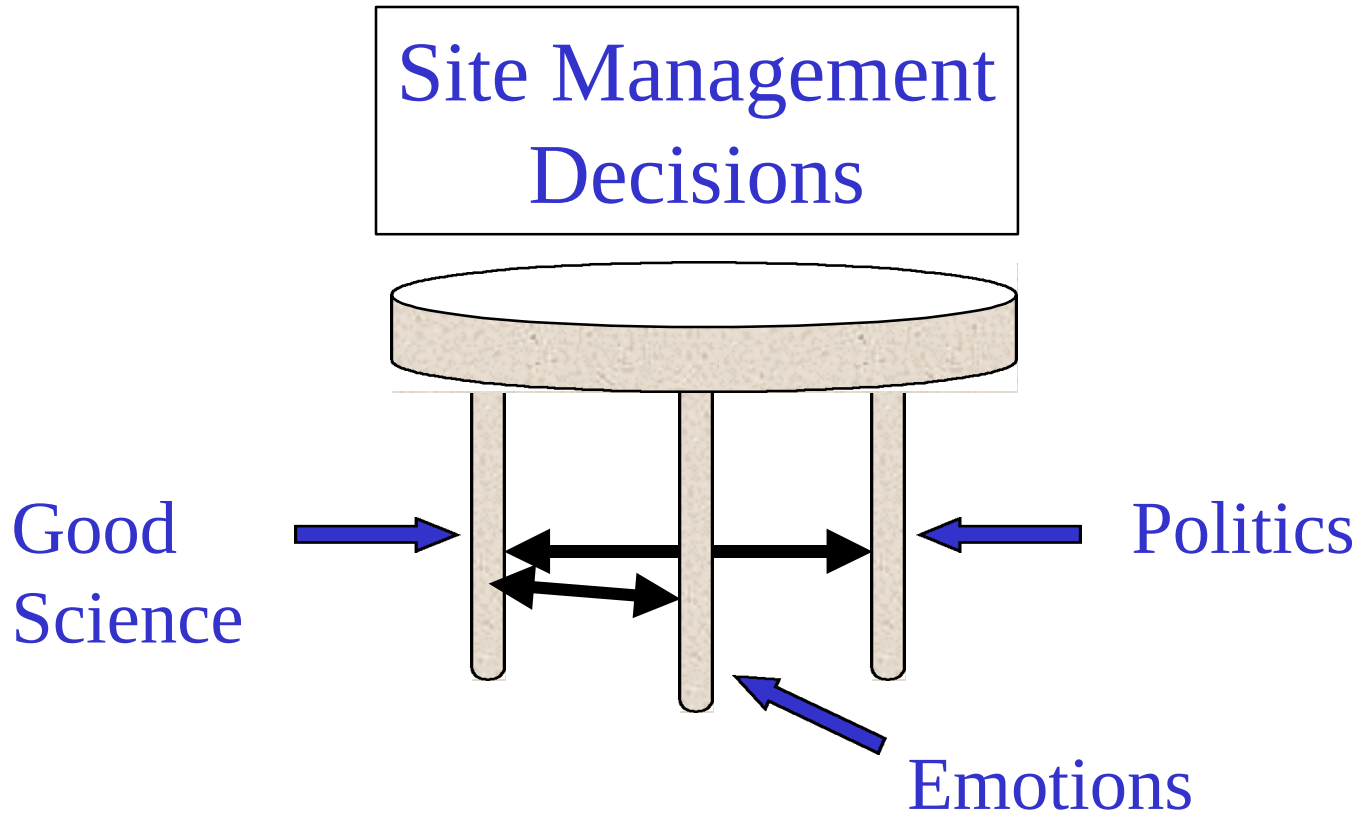
Status - Success Relative to Goals

- Containment (e.g. physical/hydraulic control, natural attenuation...) (Yes)
  - Renovation (free product recovery, SVE,….)
    - LNAPL Pool Stabilization (Yes)
    - Reduce Source Longevity (Yes, but is it significant?)
    - Reduced flux to receptors (no)
  - Restoration
    - ??????

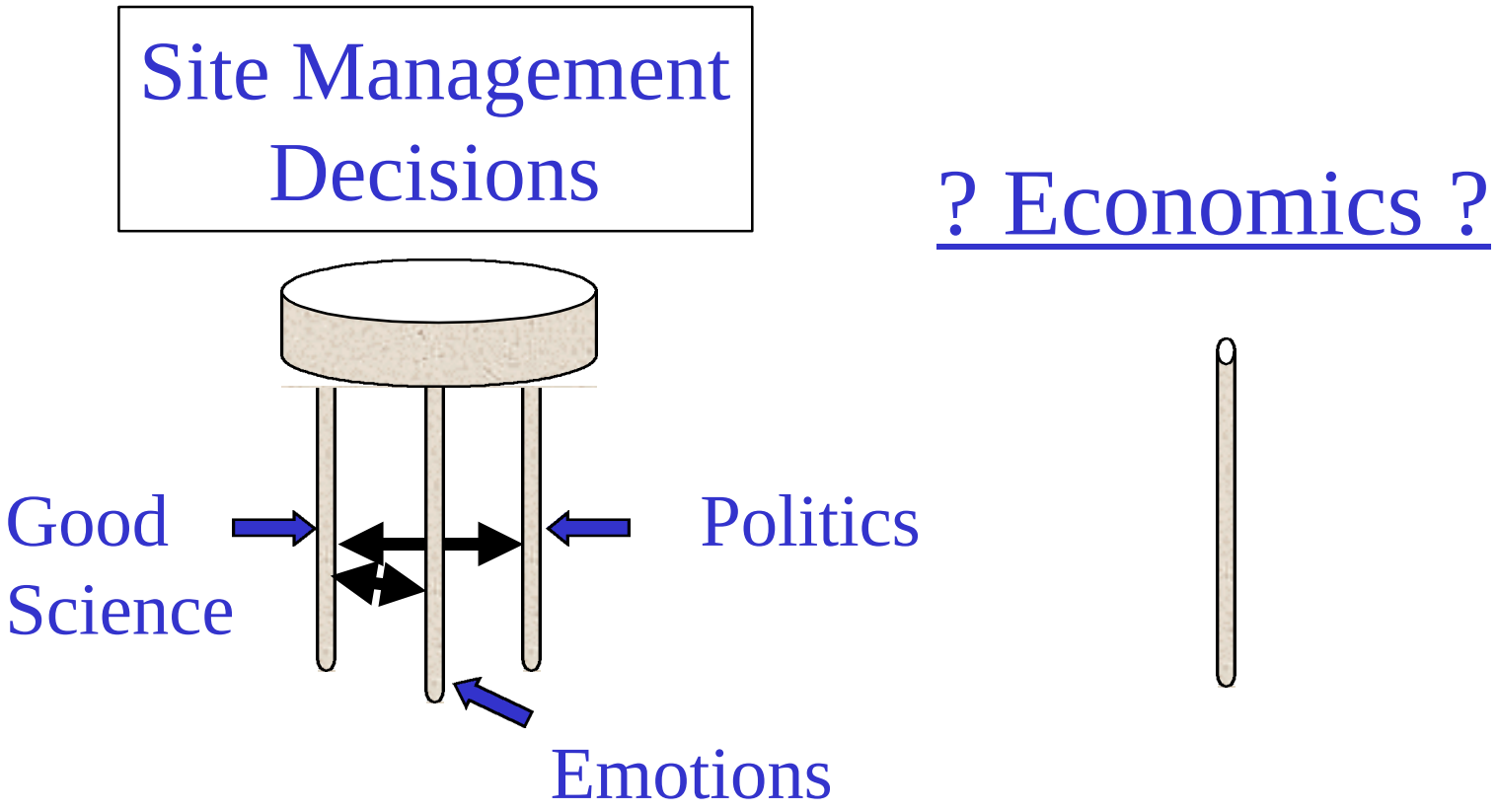
"Good Science" and Decision Making (current condition)



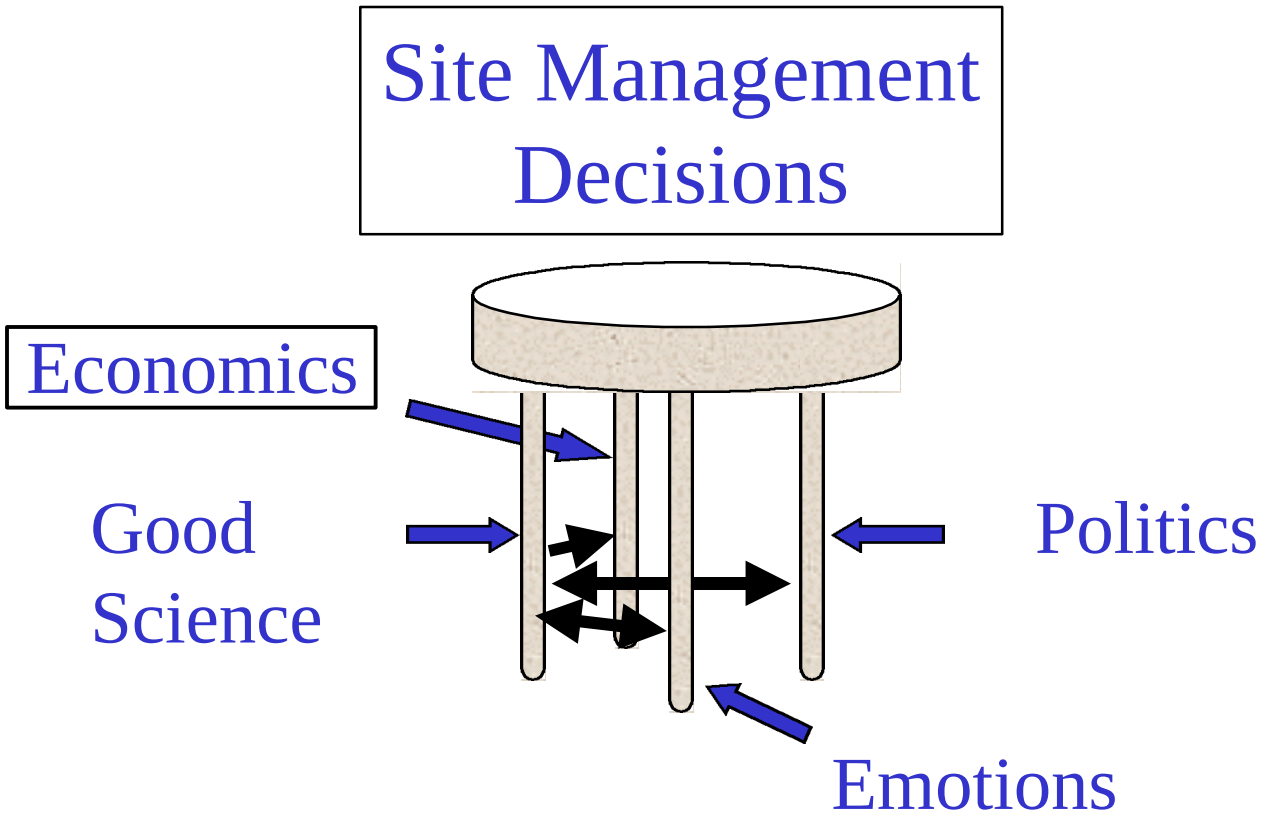
"Good Science" and Decision Making (desired condition)



"Good Science" and Decision Making (a missing element?)



"Good Science" and Decision Making (an improved approach)



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What Are We Up Against

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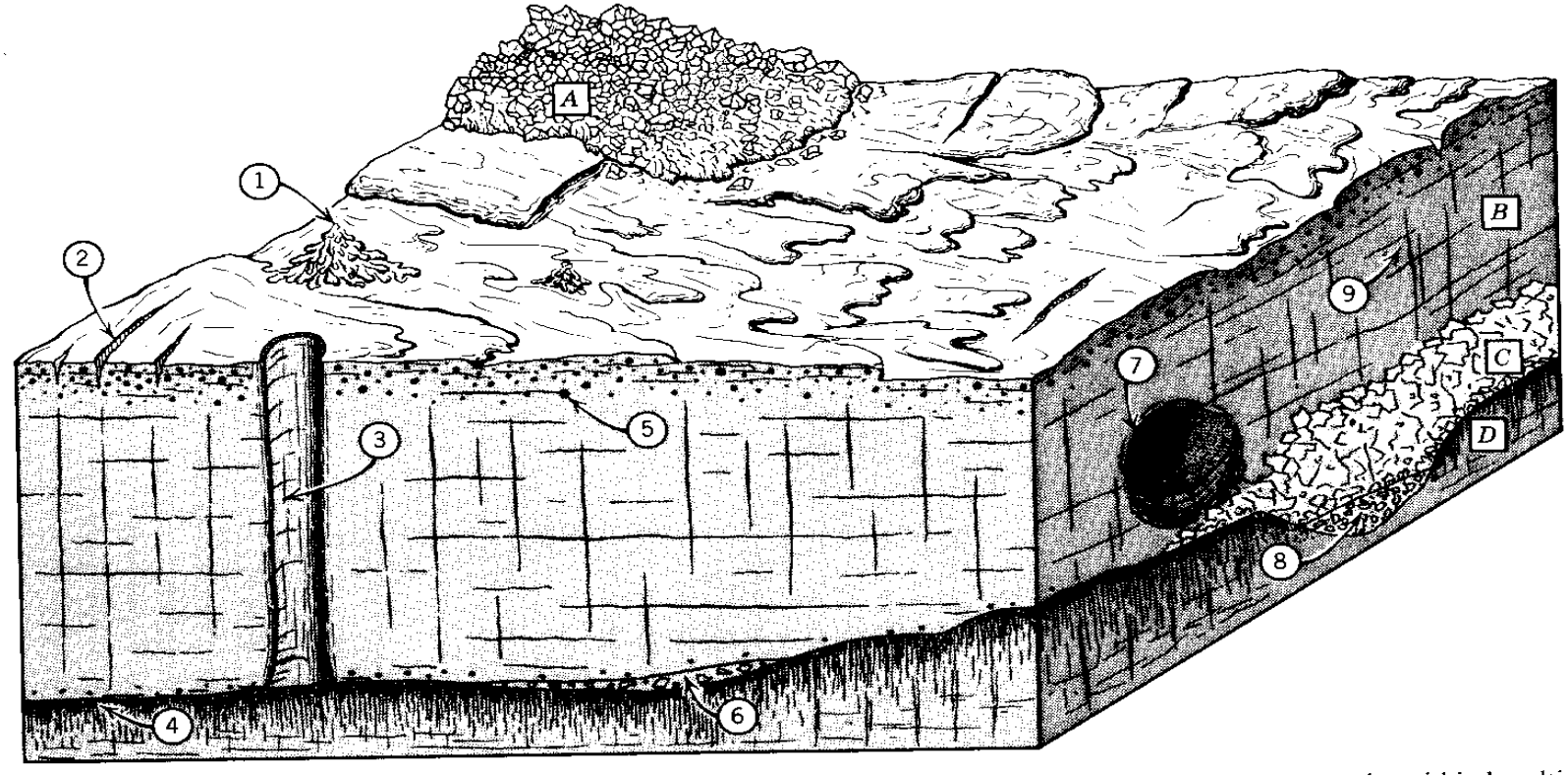
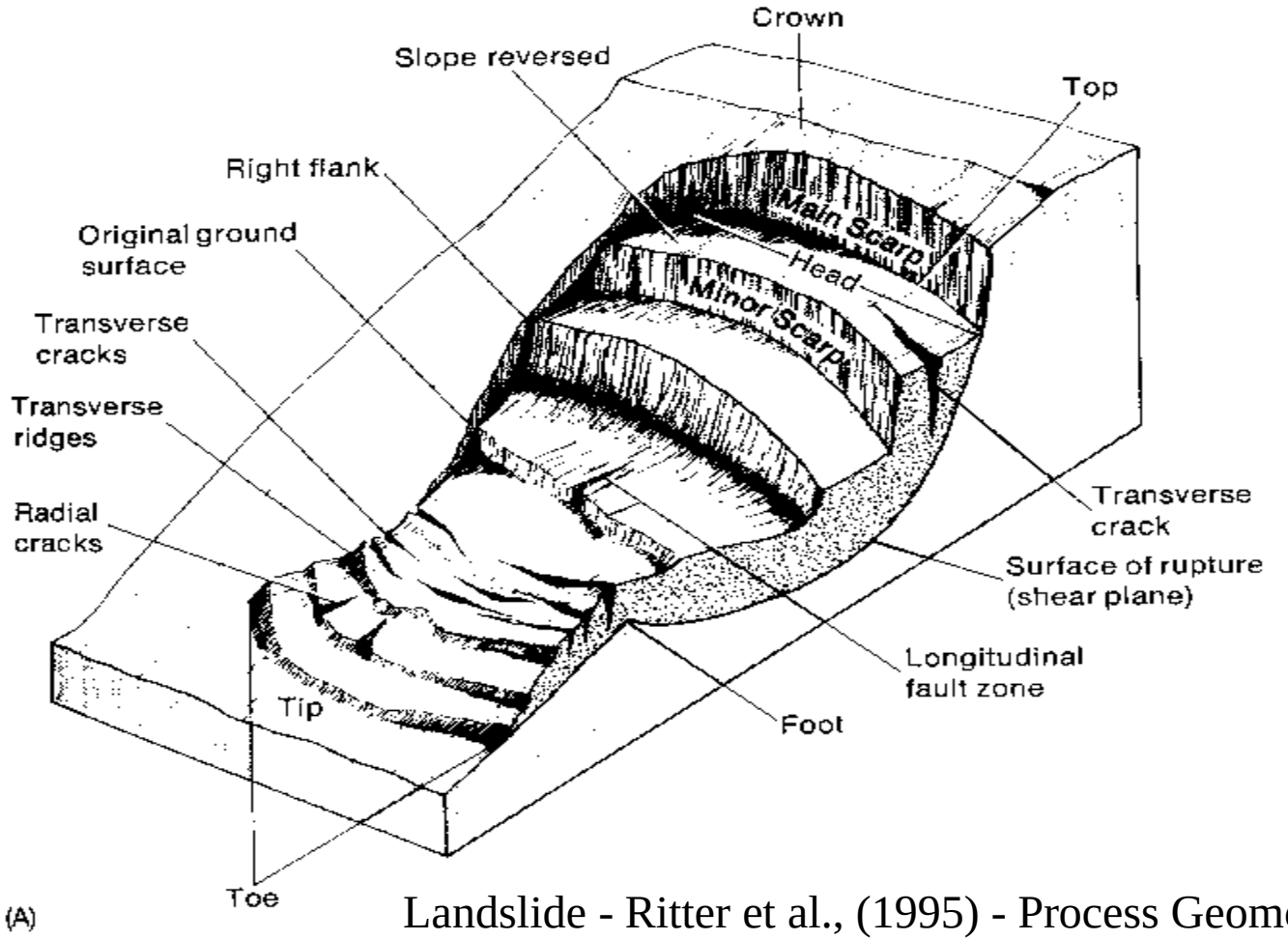
Volcanic Flow- Davis and DeWeist, 1960 - Hydrogeology





Landslide - Ritter et al., (1995) - Process Geomorphology

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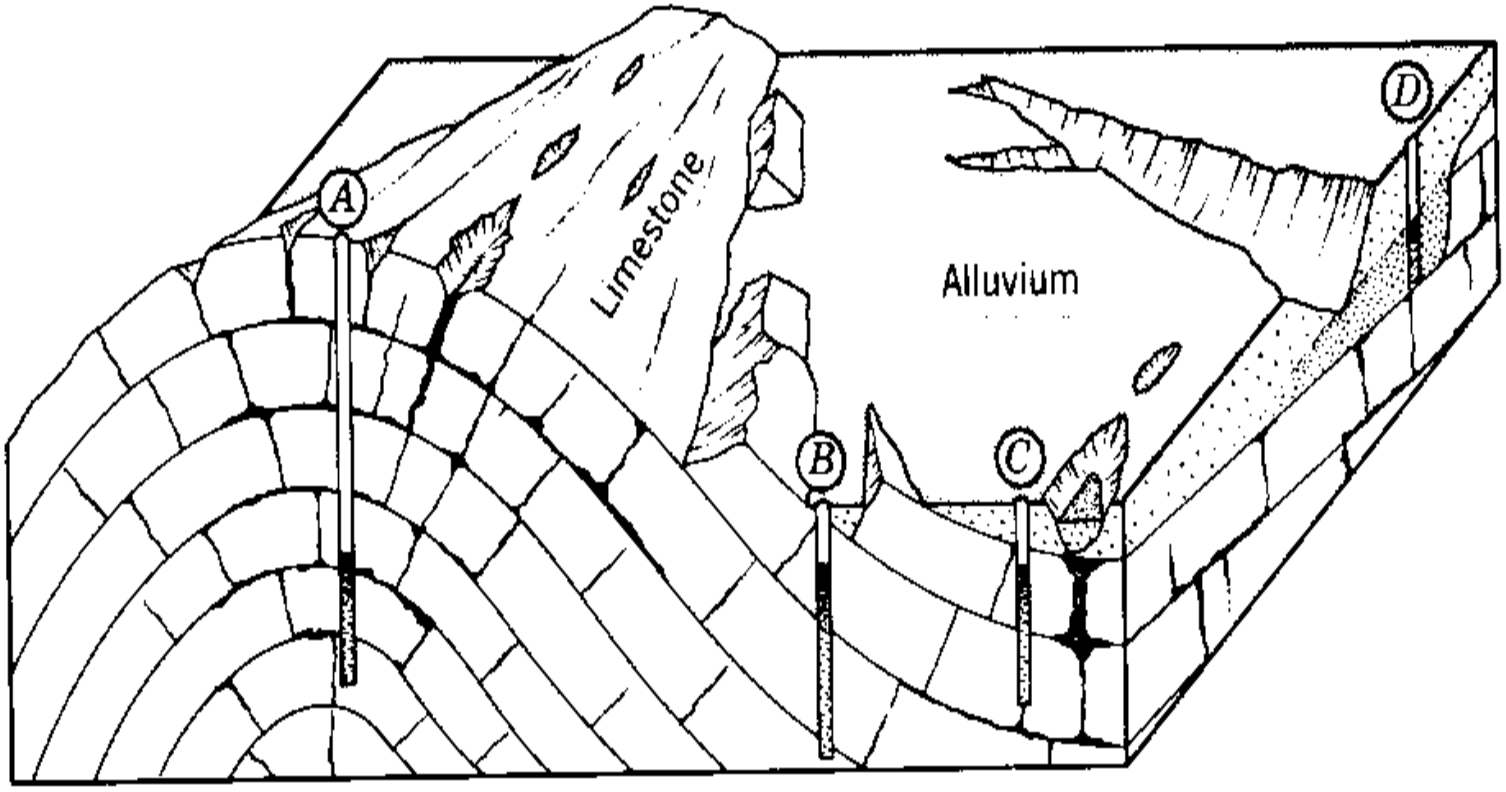
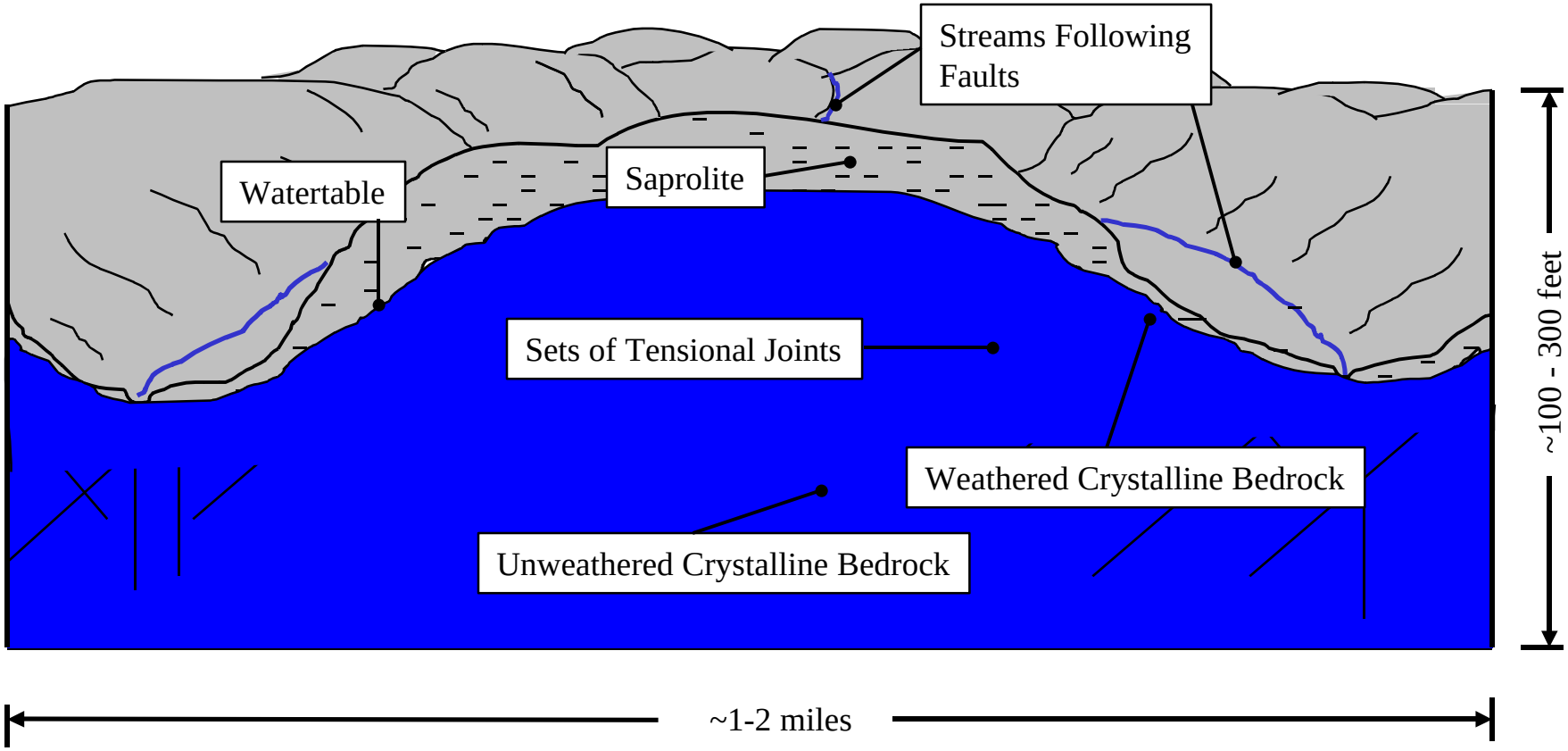
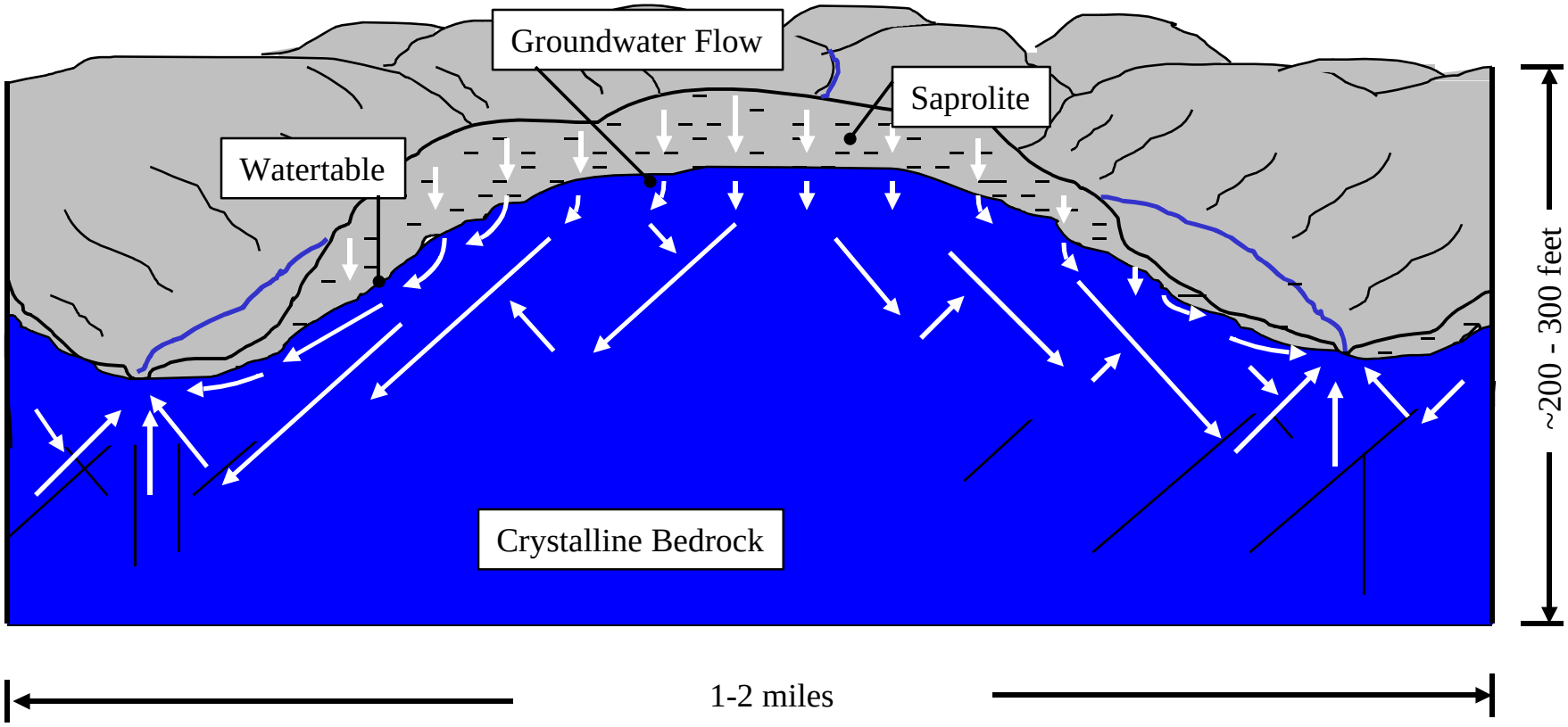
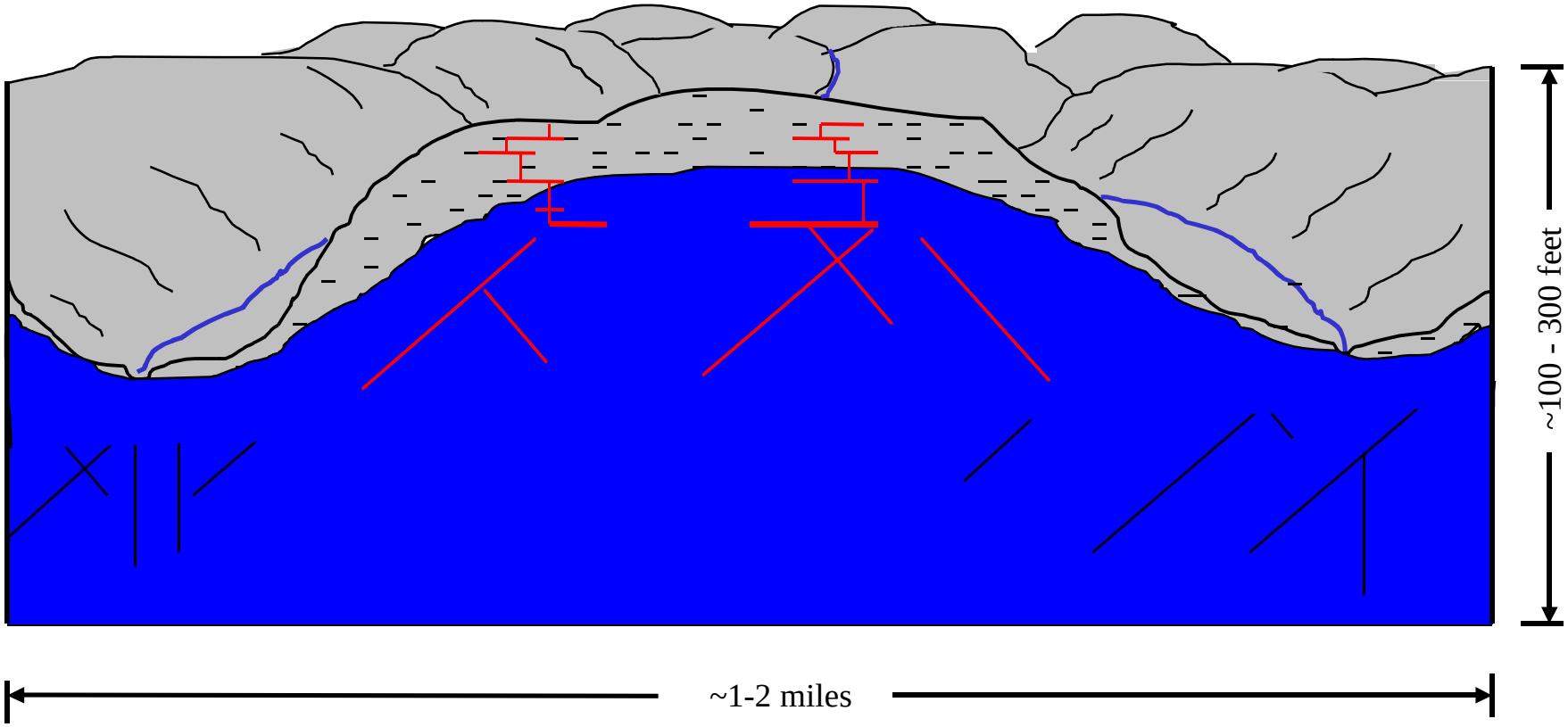
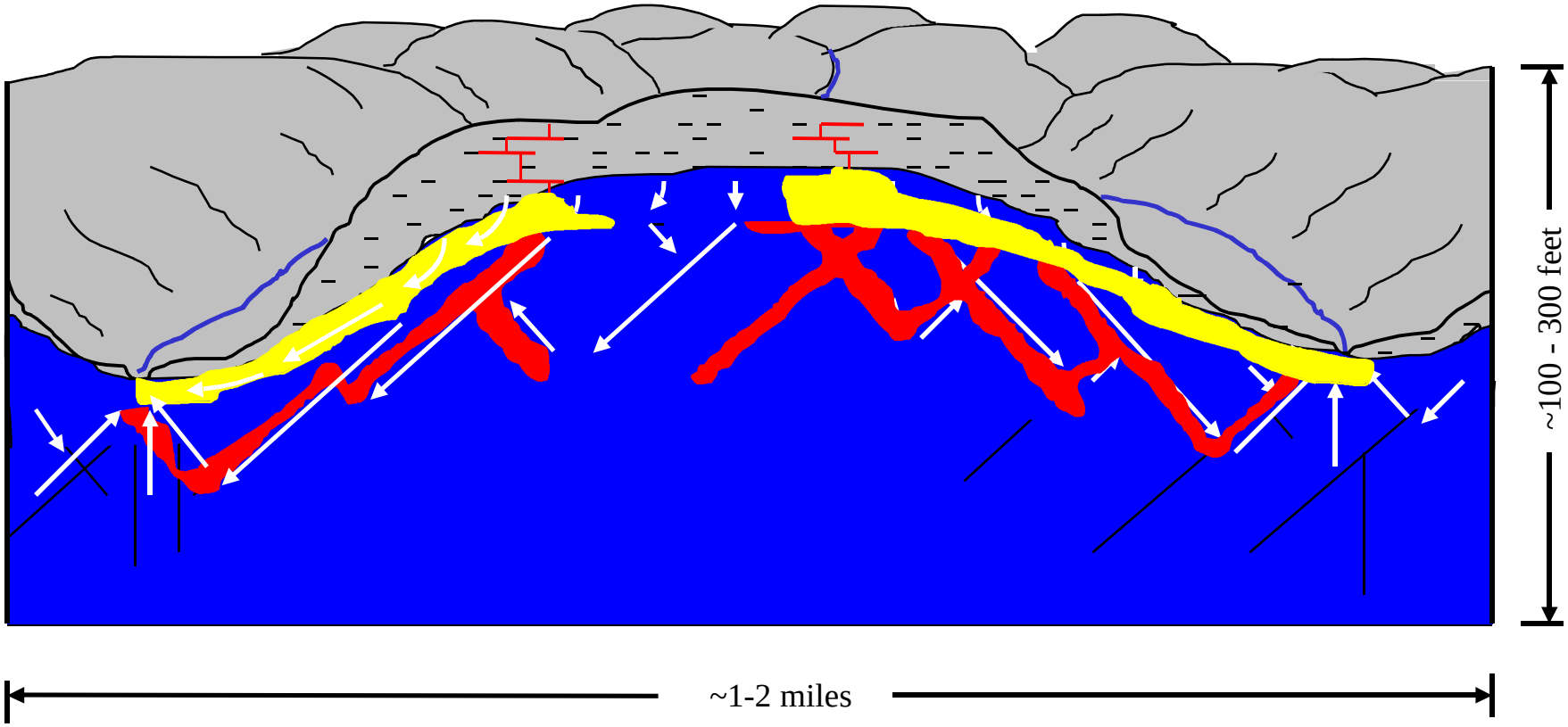
Folded Limestone - Davis and DeWeist, 1960 - Hydrogeology



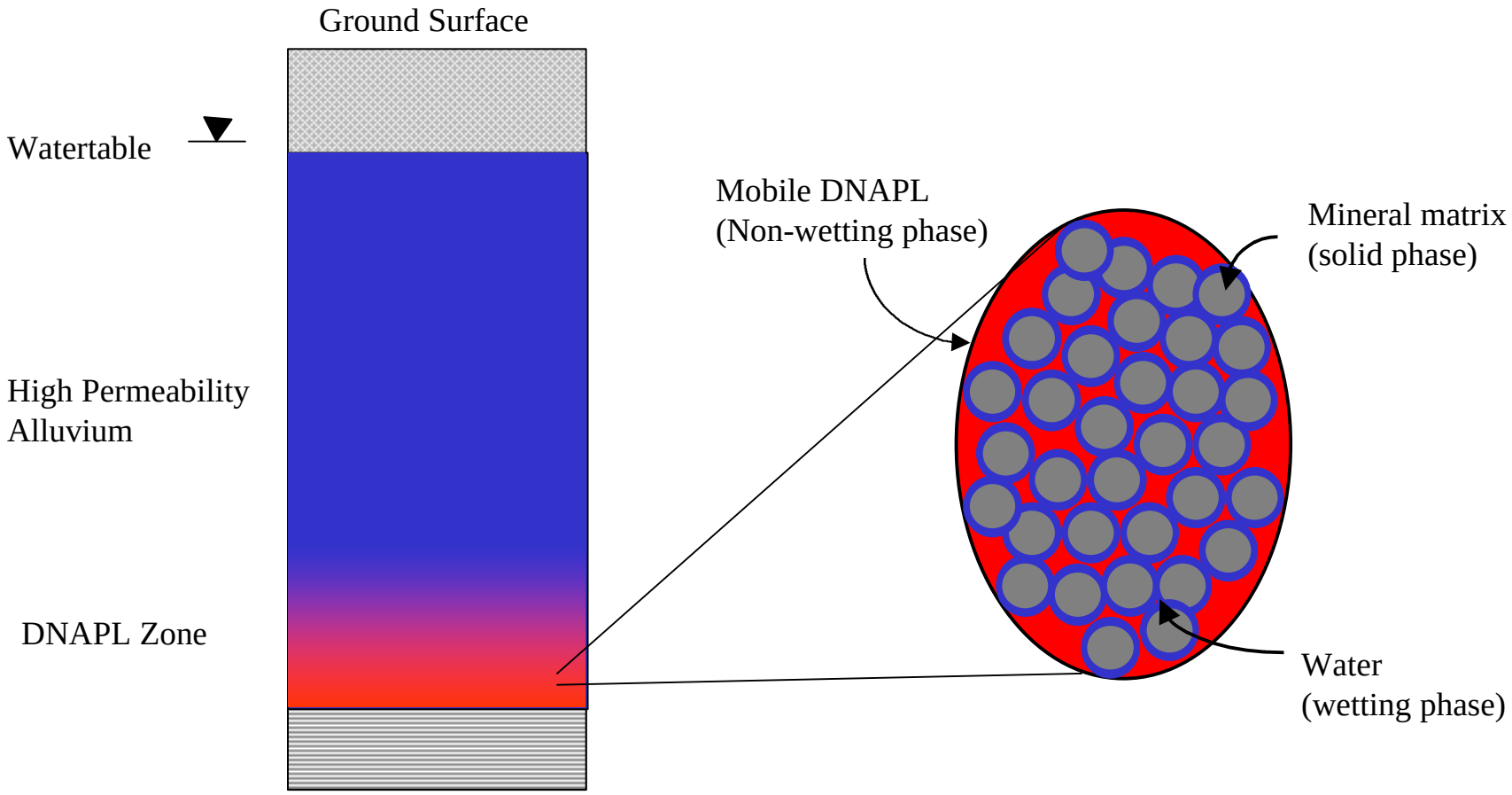

Streams Following Faults
Watertable
Saprolite
Sets of Tensional Joints
Weathered Crystalline Bedrock
Unweathered Crystalline Bedrock
~100 - 300 feet
~1-2 miles


Groundwater Flow
Saprolite
Watertable
Crystalline Bedrock
~200 - 300 feet
1-2 miles

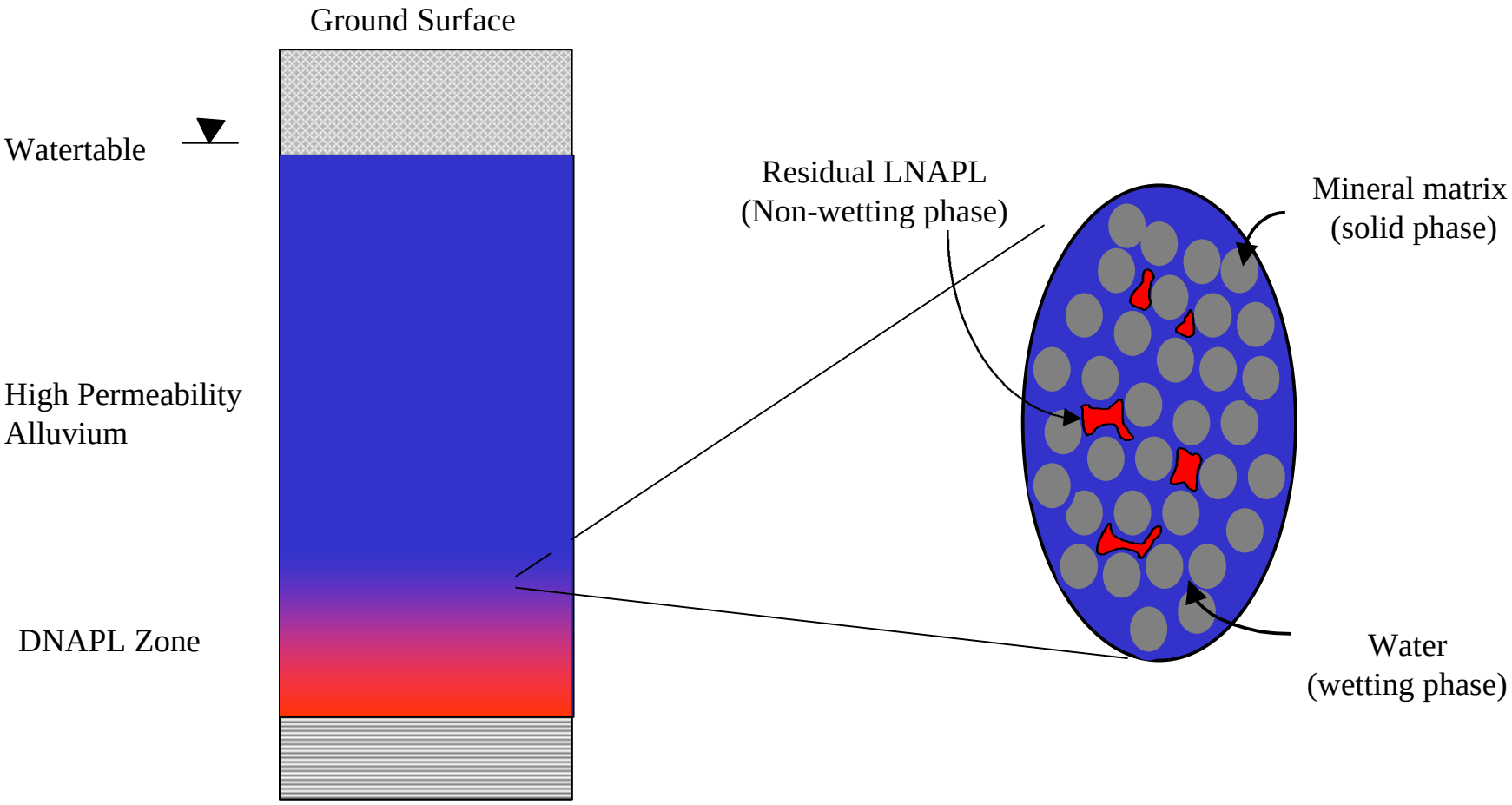

~100 - 300 feet
~1-2 miles


~100 - 300 feet
~1-2 miles

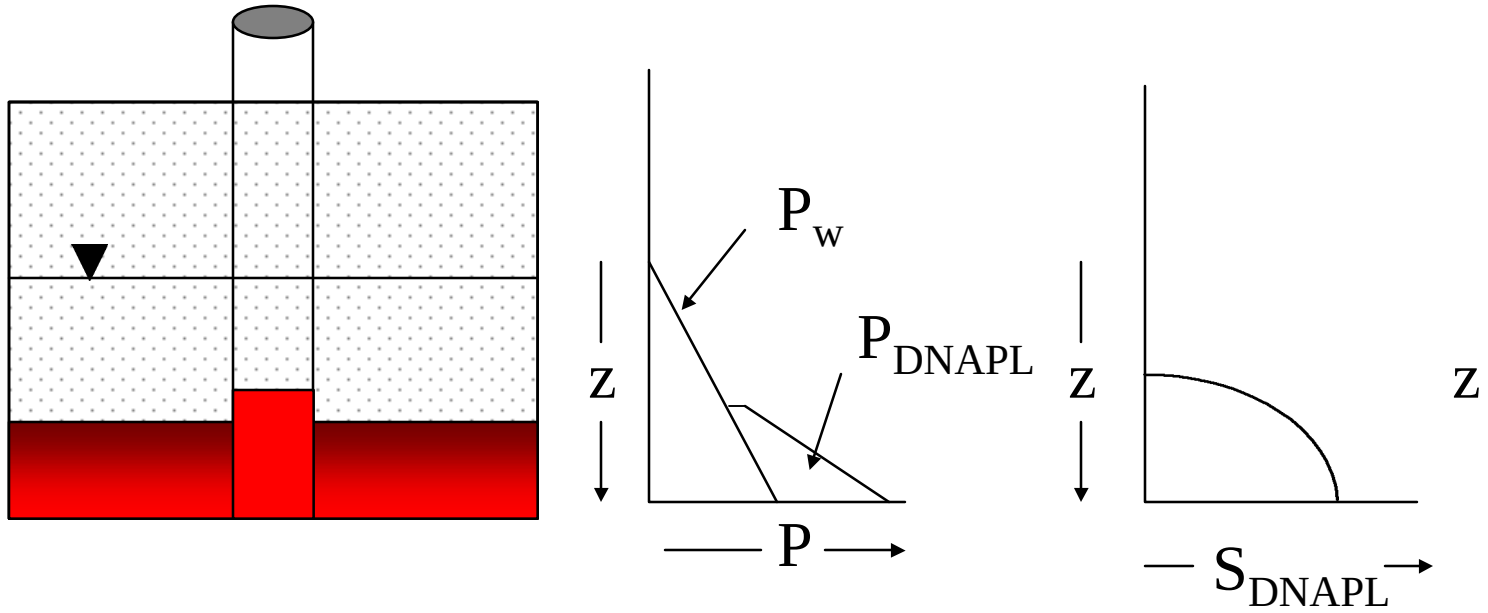
Mobile DNAPL (Potentially)



Residual DNAPL (Immobile)



Observed DNAPL Thickness in well and actual DNAPL volume



$$P_c = P_{DNAPL} - P_w$$

$$V/Area = \int_{z_1}^{z_2} S_{DNAPL} \; f \, dz$$

Kueper and McWhorter (1991)

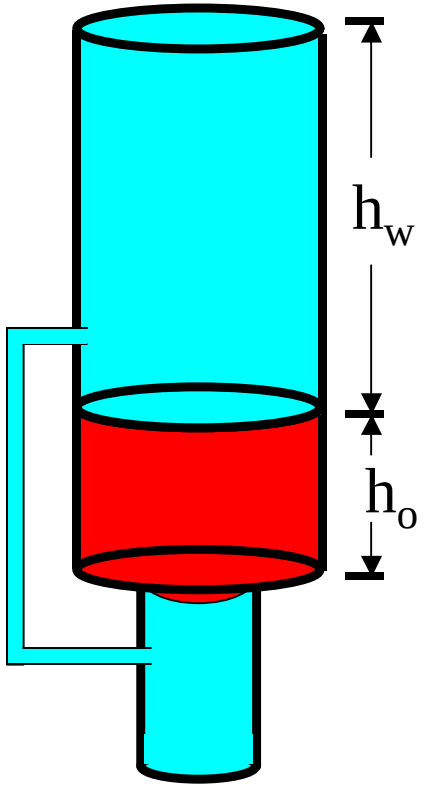
Displacement Pressure

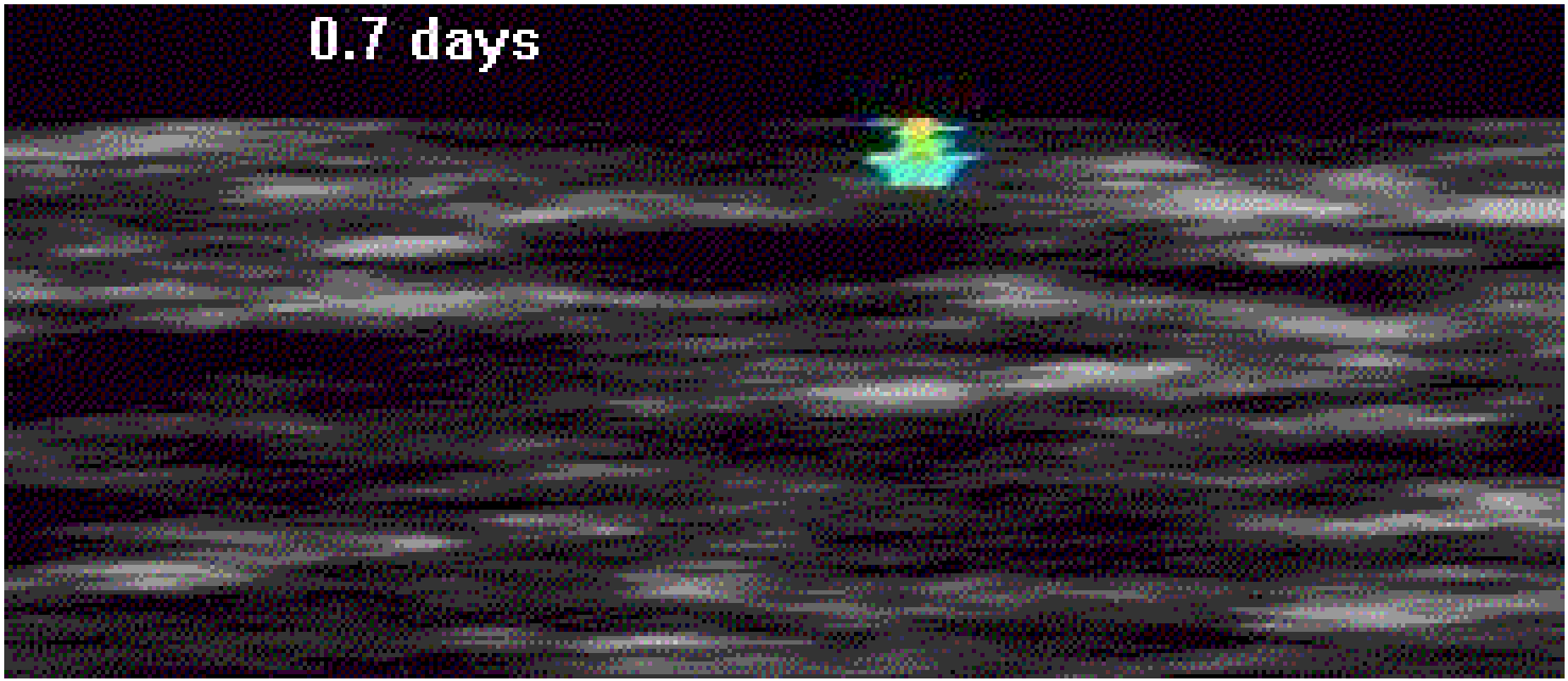
$$P_d = \frac{s_{ow}}{s_{aw}} 1.34K^{-0.43}$$

$$h_o(K) = \frac{1}{\Delta rg} \frac{s_{ow}}{s_{aw}} 1.34K^{-0.43}$$

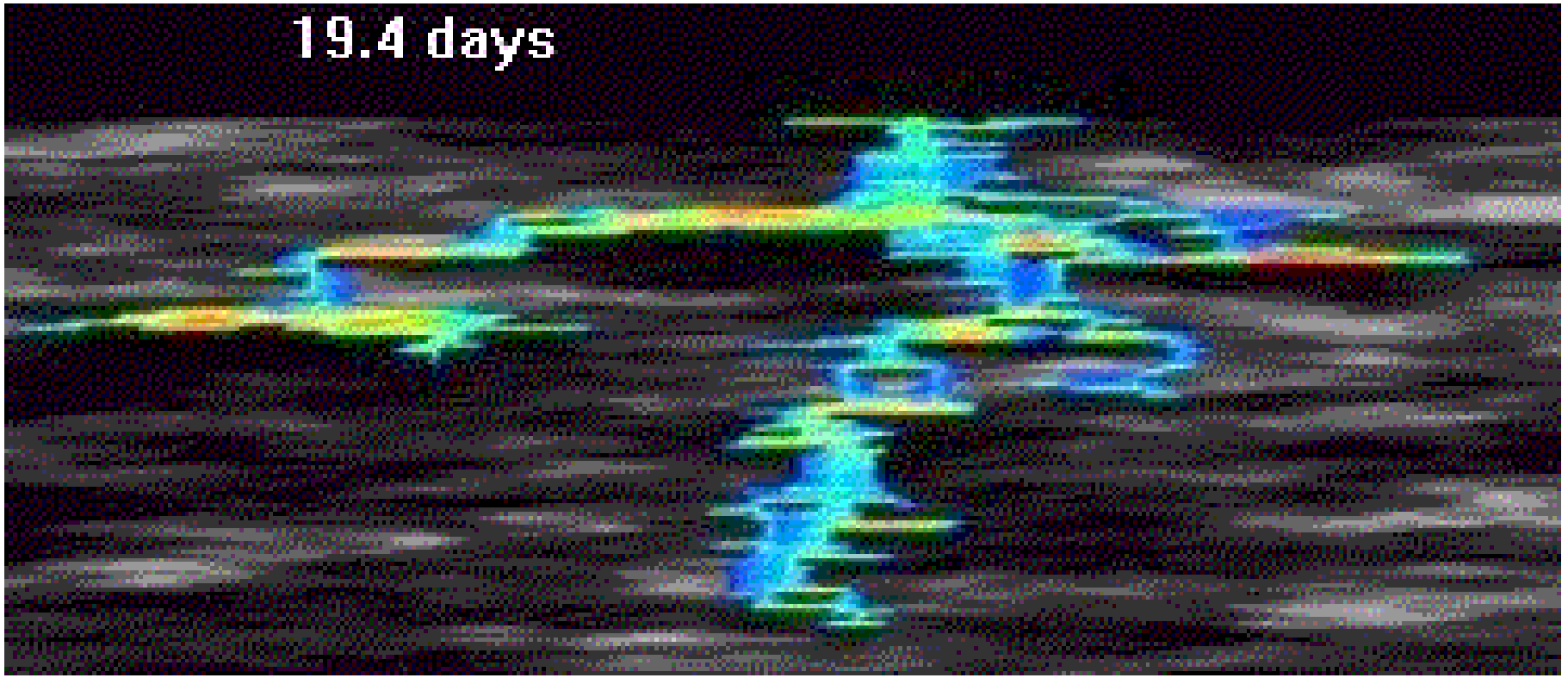
$$h_o(10^{-1} cm/\sec) = 2.5cm$$

$$h_o(10^{-7} cm/\sec) = 970cm$$





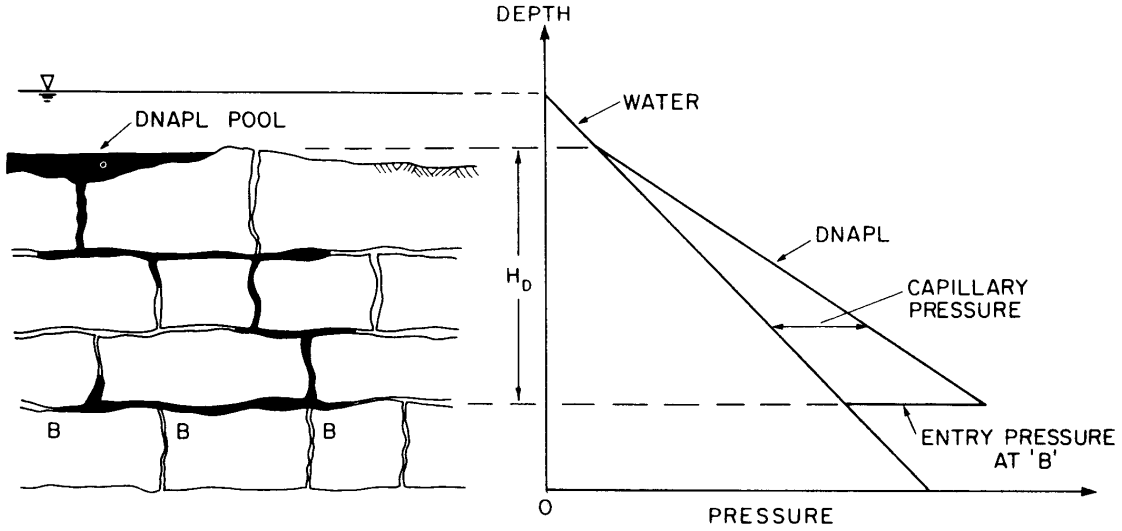
Gephard and Kueper



Gephard and Kueper

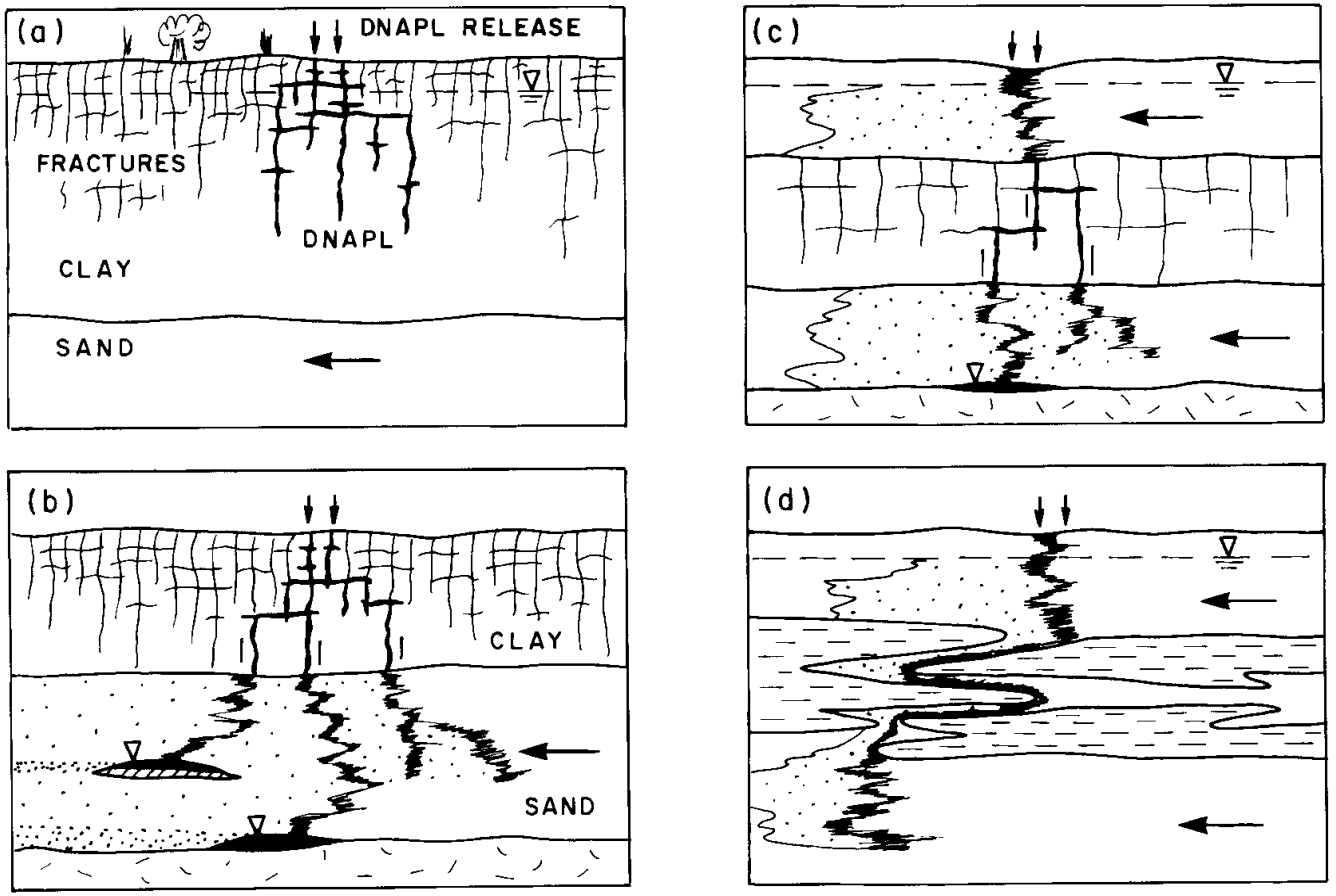
Distribution

- **Preferential migration along largest fracture apertures and/or pore throats**
- **Exclusion of DNAPL from small apertures and pore throats (Capillary Barriers)**



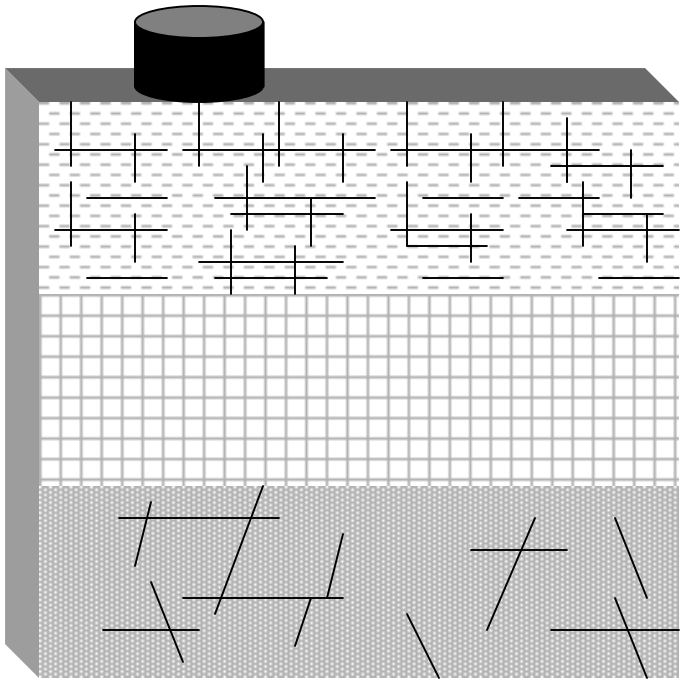
Kueper and McWhorter (1991)

DNAPL in Fractured and Layer Systems



Pankow and Cherry 1996

Plant 6 - Release Scale Conceptualization

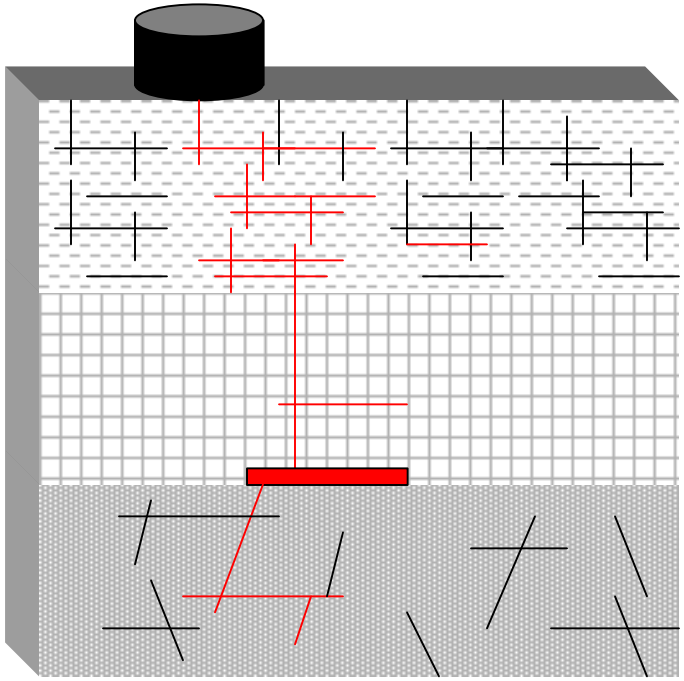


saprolite

weathered crystalline rock

unweathered crystalline rock

Distribution of DNAPL



saprolite

weathered crystalline rock

unweathered crystalline rock

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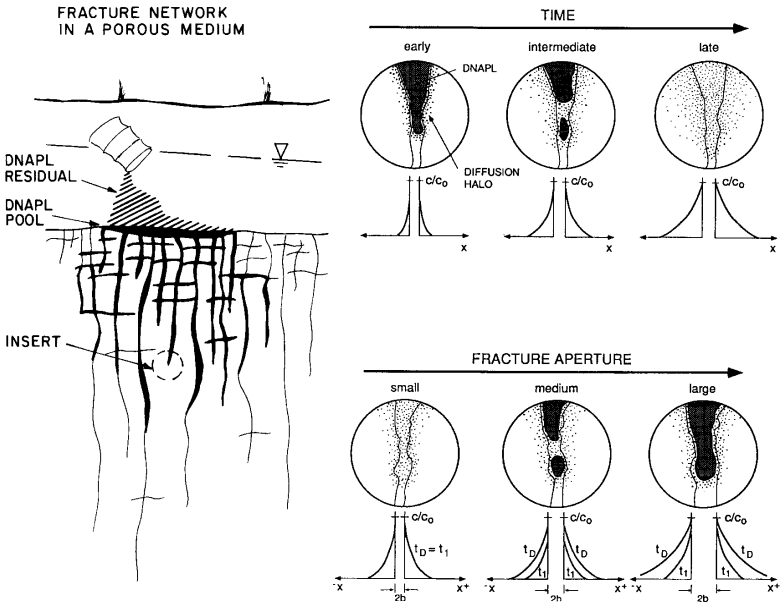
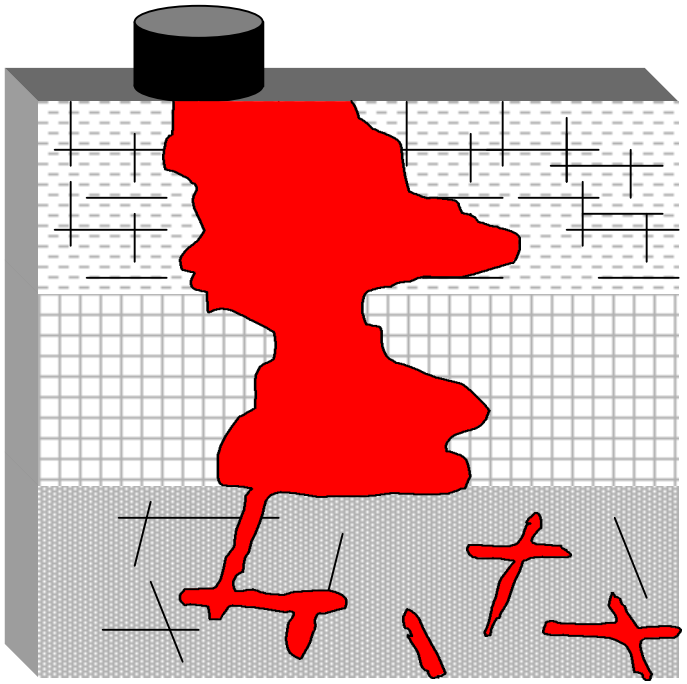
Matrix Diffusion



Pankow and Cherry 1996

- **Steep aqueous phase concentration gradients lead to diffusion into stagnant matrix blocks**
- **Due to small f_{frac} / f_{matrix} complete DNAPL depletion may occur**
- **Outward diffusion is a slow process**

Formation of Dissolved Plumes



saprolite

weathered crystalline rock

unweathered crystalline rock

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Typical Mass Depletion

(Renovation)

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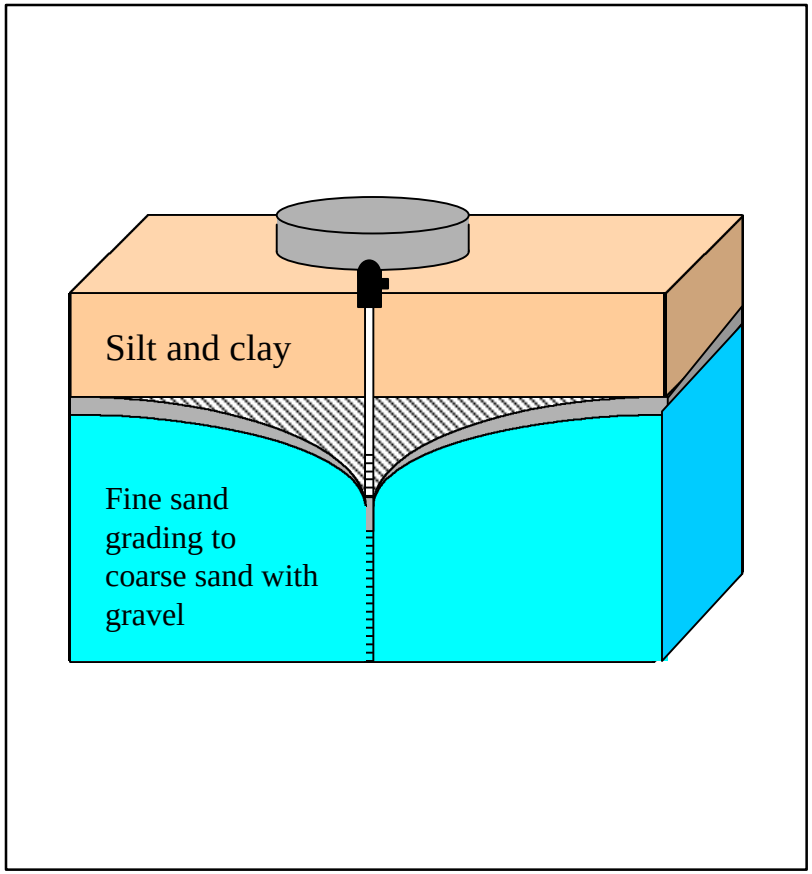
Convention Dual Phase Recovery



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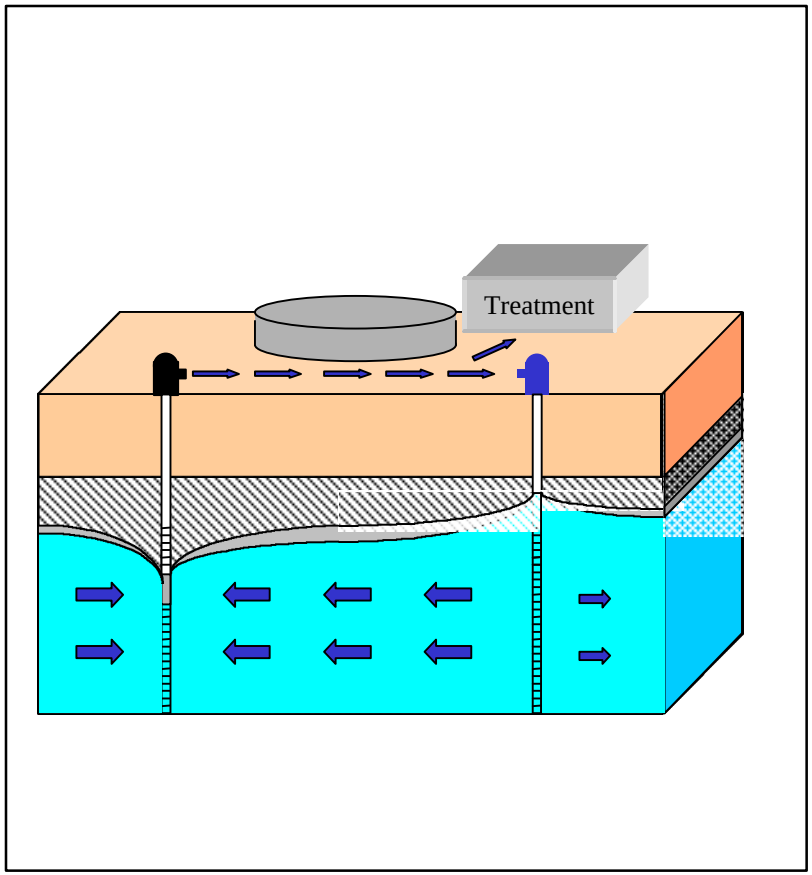
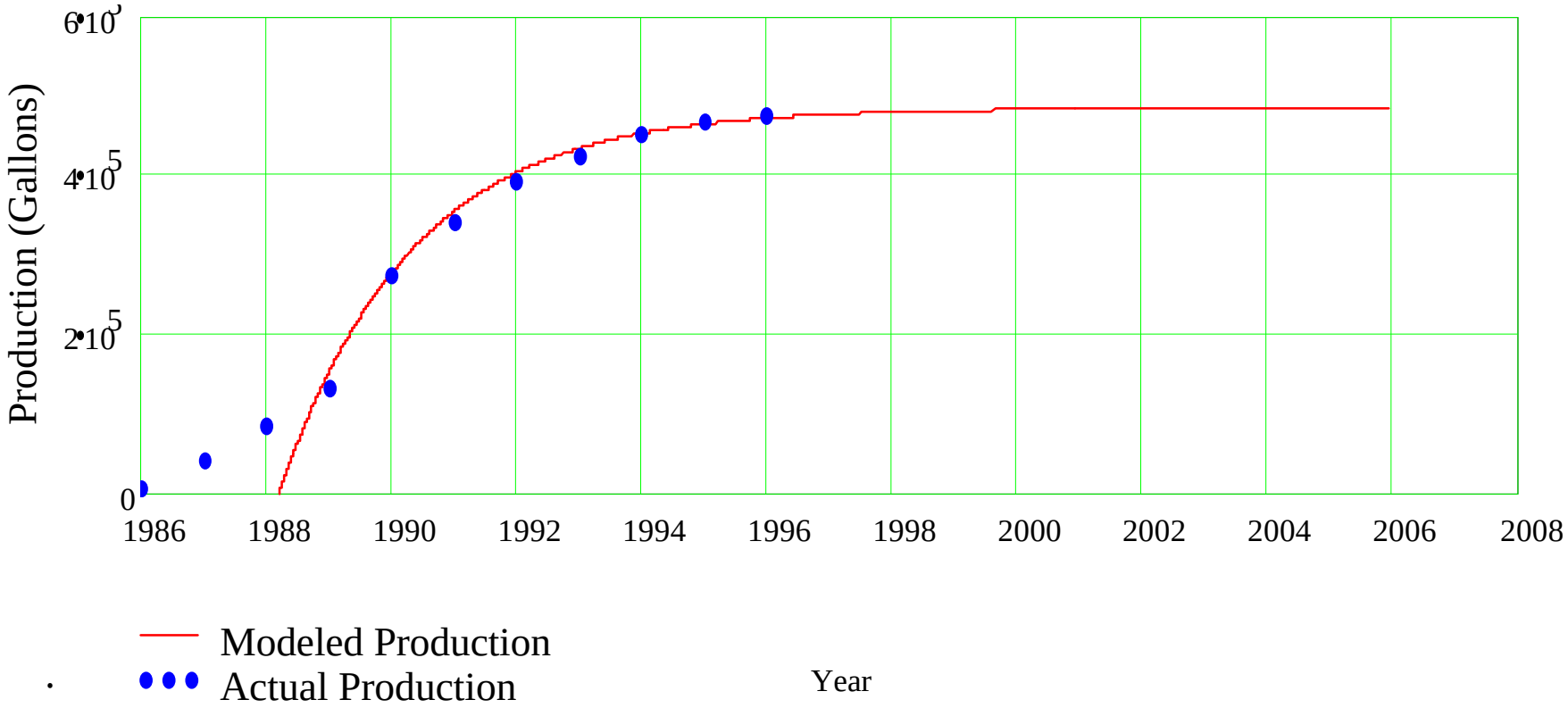
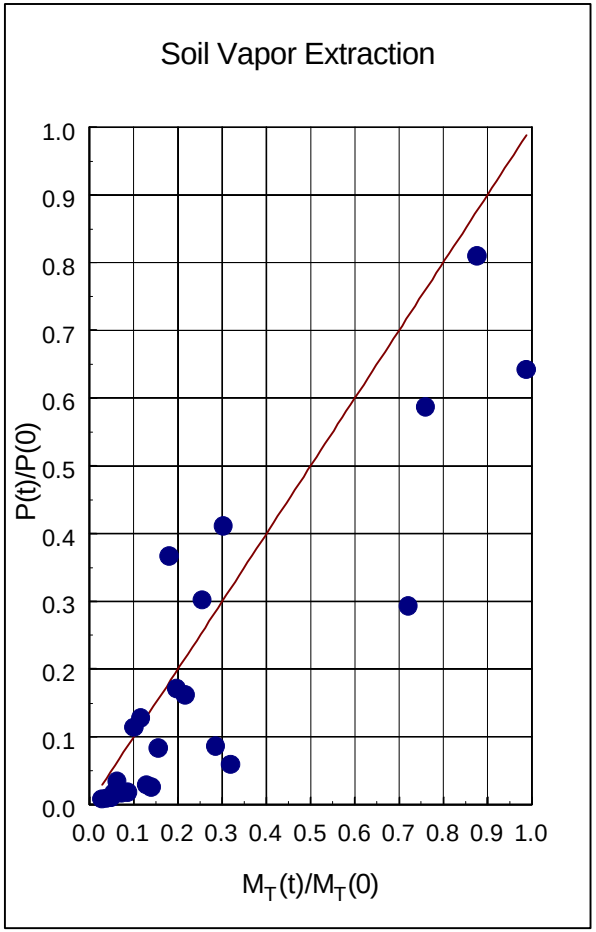
Waterflooding

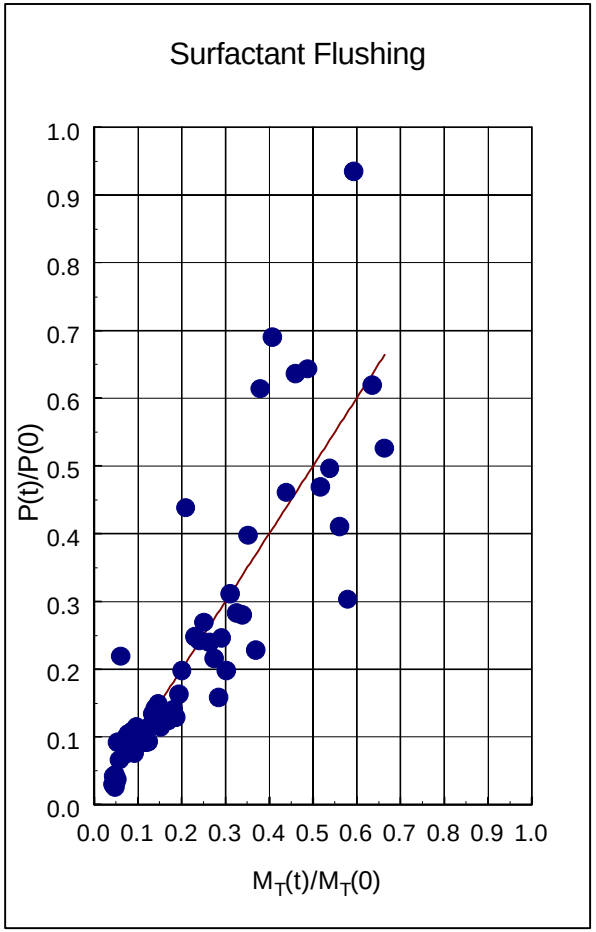


- Cycling of produced water to enhance recovery
- Increased rates of product recovery
- Improved sweep efficiency

What we see


6•10^5
4•10^5
2•10^5
0
Production (Gallons)
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
Modeled Production
Actual Production


Soil Vapor Extraction
P(t)/P(0)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
$M_T(t)/M_T(0)$


Surfactant Flushing
P(t)/P(0)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
$M_T(t)/M_T(0)$

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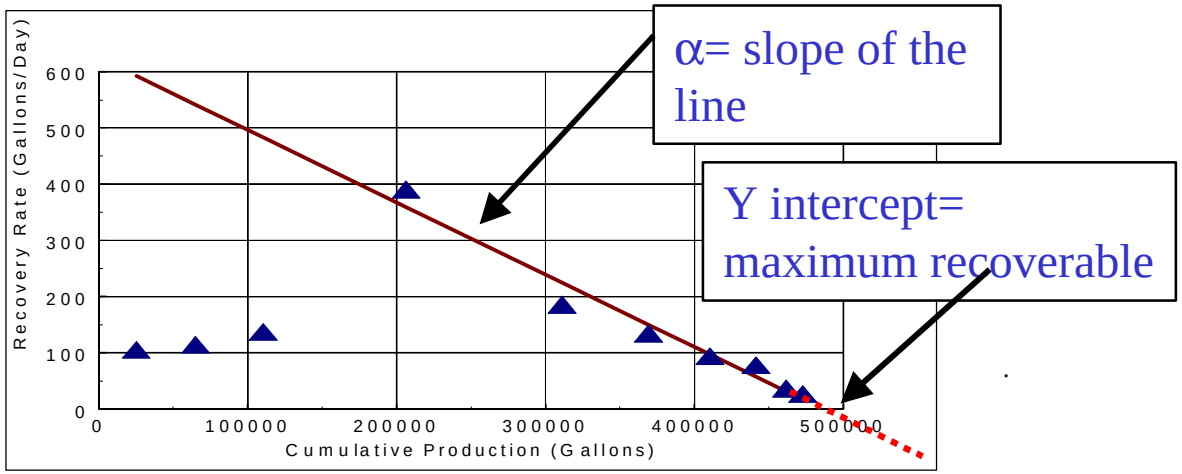
$$P(t) = -aM_{recoverable}\, e^{-at} \qquad (6)$$

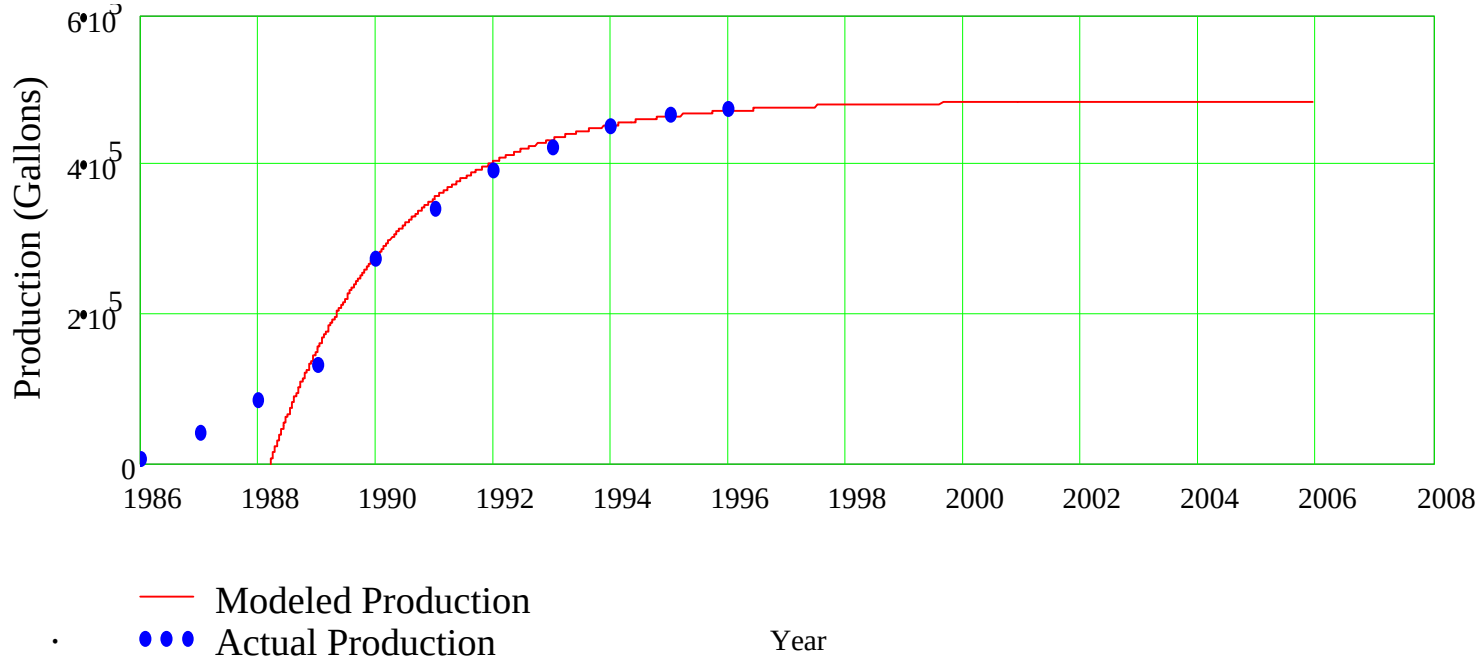
$$M_{remaining}\ (t) = M_{recoverable}\ (1 - e^{-at}) \qquad (7)$$

$$t_{1/2} = \frac{0.693}{a} \qquad (8)$$

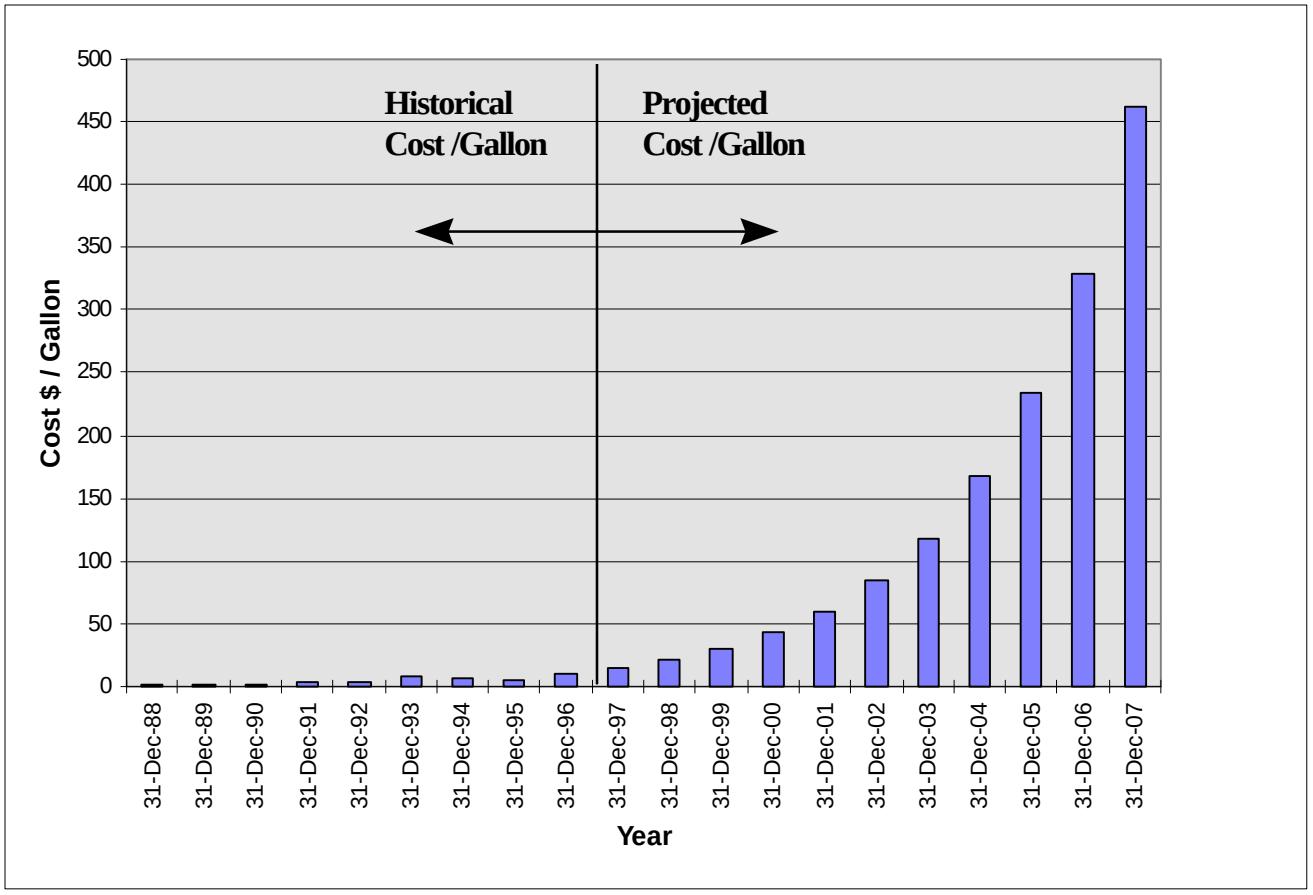


Decline Curve Analysis

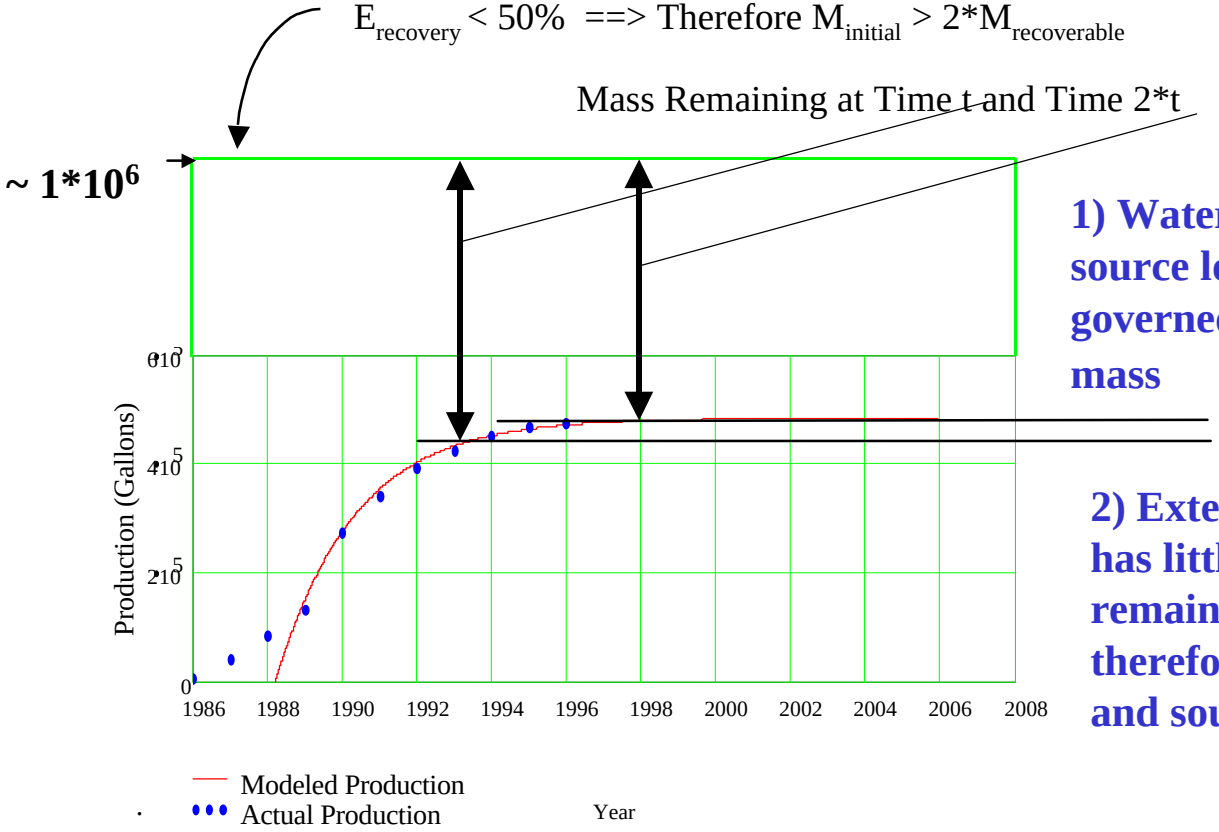
(Dual Phase Mobile LNAPL Recovery)



Cost/Gallon as a Function of Time



What we don't see



1) Water quality and source longevity are governed by remaining mass

2) Extended operation has little impact on remaining mass, and therefore Water quality and source longevity

3) Mass remaining that results effects a meaningful improvement in water quality or reduction in source longevity